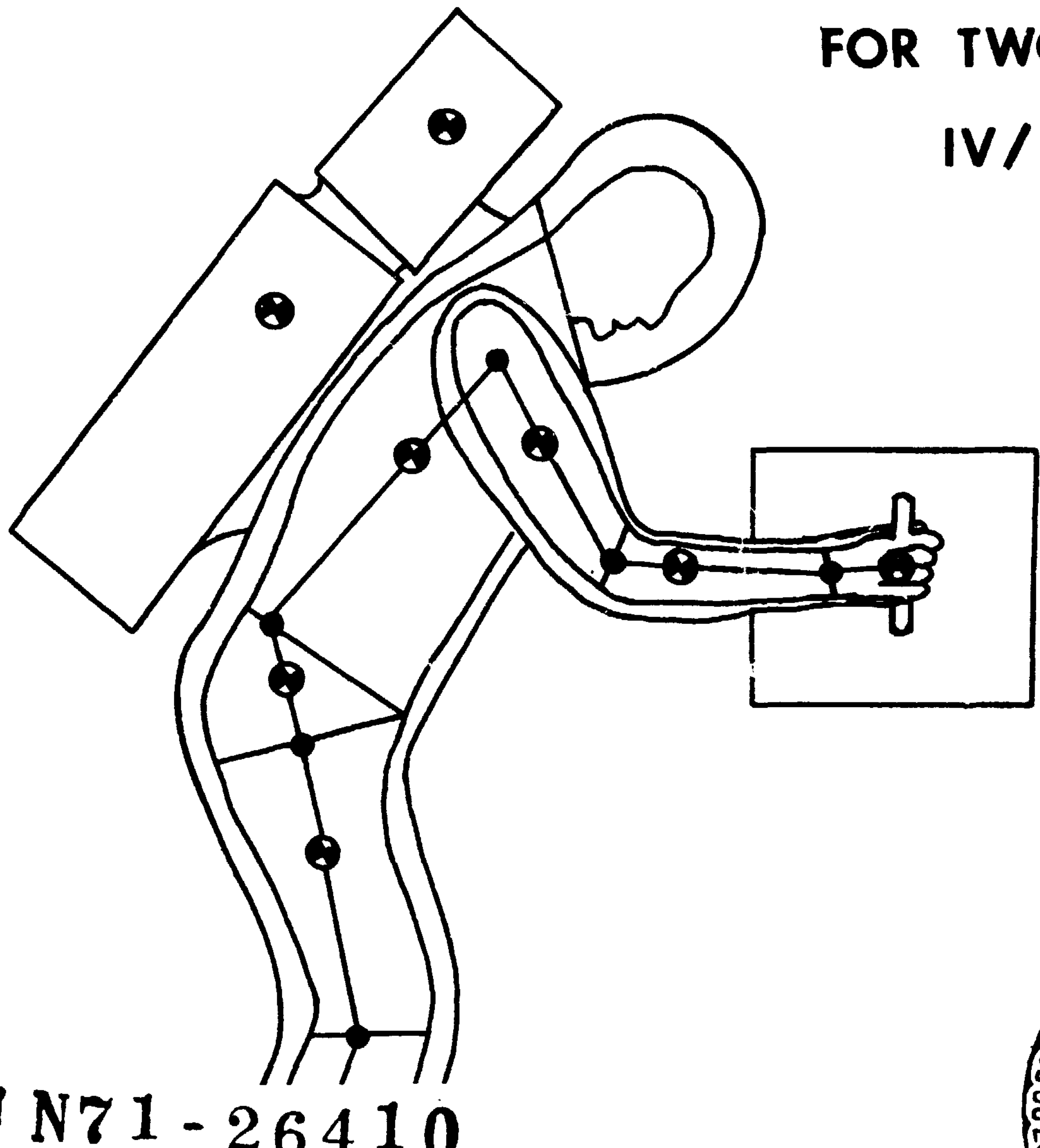
PHASE ONE REPORT

GRAPHICAL PREDICTIONS OF

HUMAN STRENGTHS

FOR TWO HANDED IV/EVA's



INDUSTRIAL ENGINEERING HUMAN PERFORMANCE GROUP
THE UNIVERSITY OF MICHIGAN

FOR

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PHASE ONE REPORT

GRAPHICAL PREDICTIONS
OF
HUMAN STRENGTHS
For Two-Handed
IVA/EVA Tasks

by

Engineering Human Performance Laboratory

The University of Michigan

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for

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Don B. Chaffin, PhD.

Project Director and
Associate Professor of
Industrial Engineering

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Two-Handed Lifting, Pushing, and Pulling Strength Predictions for Differing Gravities, Populations, and Space Suit Conditions

I. Introduction

What is human strength? What aspects of human anatomy affect it? What environmental conditions change its magnitude? How can it be predicted? These questions are often asked by persons wishing to design future physical environments in which the possibility that a fellow human being would, 1) be unable to carry-out a specific physical task, or 2) would injure himself trying to perform the task,would be reduced.

For this report, the definition of "human strength" will be considered to be the maximum force that a well-motivated individual can average for a period of approximately four seconds when using both hands to push, pull, or support (slowly lift, lower, or carry) an object. This definition has been used throughout the research which is the basis for the later reported strength predictions. Thus, the human strengths predictions herein presented represent "short-term" occasional exertion limits. For a person to repeatedly reach the predicted strengths, it is suggested that a minimum of five minutes rest would need to transpire between exertions to avoid muscle fatigue. [1]

[1] It is suggested that the reader refer to a paper by Kroemer, 1970, for further definitions of muscle strength and endurance.

Factors Affecting Human Strength

Many complex variables act to affect the two-handed strength outputs for a population. When comparing different individual's strengths, each individual's past physical training is important. Doubling of normal human strength through a rigorous strength training program is not uncommon.

If a person is large, as dictated by both height and weight, he often has a strength advantage over a smaller individual in that he has a greater selection of body positions when reaching-out and exerting a force on an object, as well as having a greater mass to provide a counterweight for body balance maintenance. At the same time, however, the larger individual is somewhat at a disadvantage when hand forces are exerted close to the body, since his longer extremeties cause greater rotational moments which then must be counteracted by his muscles.

Ageing, in general, has been found to significantly affect the population's strength. Assmussen (1956) has shown a gradual decline in strength of the male population after age 30, reaching 84% of its prior value at age 60. It should be quickly noted that such a population effect is highly dependent upon the daily physical activities of the individuals comprising the population. A strength training program would probably negate this effect.

A person's motivation to perform a strength requiring task is also a critical factor. Increases of 25% in strength have been reported by Ikai and Steinhaus (1961), when post-hypnotic suggestion was used to encourage increased performance. Hence, strength predictions, such as developed in this report, are conservative estimates of a person's physiological limits. For the present, because the motivation variable is so difficult to manipulate, it is believed that strength predictions for various tasks should not exceed the values that groups of individuals have demonstrated in laboratory strength tests. In other words, to rely on people willfully counteracting their subconscious inhibitions when performing physical tasks outside the laboratory (when they could not do so in the labcratory) will not be justified until the nature of the motivation variable is better defined.

The speed at which an object is moved can be a contributing factor in muscle strength development. One basis for this is that a muscle loses its tension capability when simultaneous shortening occurs.[1] In addition, a dynamic movement involves accelerations and decelerations of both the body masses and any mass being moved. Hence the accelerations develop additional forces that must be compensated for by the musculature. It is worthy of note here that it has been reported by many (see Karger and Bayha, 1965) that the time taken to move weights normally increases with increased weights. Hence, if a person is allowed to exert his maximum strength slowly, which would conform to safe materials handling

[1]The reader is referred to earlier studies by Ruch, 1960 and Assmussen, 1965, for further descriptions of strength loss due to shortening contractions.

rules, the dynamic aspects are believed to be a small contributor to the overall strength predictions.

One factor that is perhaps the most important factor of all in defining human strength is the body configuration that a person is capable of achieving when pushing, pulling, or supporting an object with his hands. This is based on the combination effects of many human and environmental variables. As mentioned earlier, maximum hand force is dependent upon the person being able to maintain his body balance. If an object is located such that a person has to reach-out to lift or pull on it, then his force capability is highly dependent upon whether or not he can position his own body mass such that its weight counter-balances the force exerted on the hands. Furthermore, the muscles of the body are constructed and positioned in such a manner as to dictate force outputs that differ with the angles of the major articulations of the body. Clarke (1966) has shown that some strengths vary by as much as 2:1 depending on the angle of the body joints involved in the muscle actions.

An environmental factor that can greatly influence two-handed force capability is gravity. Under reduced gravity conditions the musculature is relieved of the need to support a person's body mass. Thus there exists the possibility for a person to use this "released" muscle capability to increase his hand force. With less body weight, however, the person becomes more "unstable," i.e., less hand force will push him over frontwards, backwards, or sideways. It can therefore be shown that for some tasks performed under reduced gravity conditions, man's strength is increased, but for others, it is decreased. This effect is a major development of the work described in this report.

From the preceding, it should also be realized that an inflated space suit with backpack (EMU mode) introduces two major effects on human two-handed strengths. First, the inflated suit causes rotational moments at the major articulations of the suit, which in turn modify the maximum rotational moments that can be produced by the muscles of an unsuited individual. These "suit torques" may help or hinder the person in producing a hand force, depending upon the body positions and direction of muscle actions at each articulation. In addition, the inflated suit restricts the range-of-motion at the various articulations. This then reduces the body positions that a person can choose from to maximize his force output. In other words, he may be forced to use biomechanically poor body configurations.

The weight of the backpack is another factor which presents both good and bad elements. Since it is a fixed mass on a person's back (i.e., it moves with the middle and upper back), a person can use the weight of it to increase the counter-balance effect when pulling or lifting in an extended reach position. This effect is especially helpful under reduced gravity conditions where body balance is the major limitation to strength development. When a person is lifting an object close to the body, however, the extra weight of the backpack simply lessens the amount of back and leg muscle capacity that is available to support the load applied to the hands. Once again, the effects of the space suit with backpack is a major presentation later in this report.

Scope of Strength Predictions

The strength predictions that comprise Sections III and IV of this report are based on simulations performed with a computerized biomechanical model developed in four previous years of strength research performed by the Engineering Human Performance Laboratory at The University of Michigan. The model (and its use) is based on consideration of all of the previously described factors.

The selection of specific conditions to be simulated involved many different individuals in both the EVA and Biomedical Branches at the Manned Spacecraft Center, and in particular the Human Factors Group.[1] In general, at the onset of this project, it was believed that the greatest design benefit would be derived from having two-handed strength predictions for physical activities which would need to be performed in a reduced lunar gravity (0.2 g.), for both shirt sleeved and suited EMU conditions. To a lesser degree, it was also believed that the design of a spinning space station could benefit, and thus an intermediate 0.7 g. condition was simulated. So as to facilitate a comparison of earth and lunar effects, a full set of activities under 1.0 g. conditions was

[1]The reader is referred to the Acknowledgements for the names of specific NASA personnel contributing to this effort.

simulated.

The physical activities chosen for the simulations are defined as follows:

*Lift: An element wherein a person is applying a force to an object which tends to move the object vertically upward. (If movement occurs, it is in the vertical direction only.)

*Push: An element wherein a person is applying a force to an object which tends to move the object away from the body in a horizontal direction.

*Pull: An element wherein a person is applying a force to an object which tends to move the object towards the body in a horizontal direction.

These activities were assumed in the simulations to be performed by persons having different size and strength characteristics, as described in Section II. To obtain an estimate of the effect of where an object is located in respect to a person's basic supporting structure (i.e., the feet), the lifts, pushes, and pulls were all simulated by systematically moving the hands about a specified area. This area was bounded by, 1) the floor, 2) the person's maximum vertical reach, 3) either a line running vertically through the ankles or the front contour of the person, and 4) the person's horizontal reach distance. These simulation boundaries are displayed in Figure 1 on the following page.

The procedure employed in each simulation was to discretely place the hands at some location inside the grossly defined reach boundaries, and then allow the computer to iterate the body configurations through the range-of-motions of each joint that provides a "connected linkage" (i.e., the hand position is within reach). For each iteration of the body configuration, a hand force prediction is made, as described in Section II. Thus at the end of a simulation run the following predictions are presented:

* For a wide range of relative hand positions, the maximum two-handed force capabilities for a statistically defined size and strength portion of the male population.

* For each relative hand position, the body configurations that allow a person to exert his maximum hand forces.

* The maximum vertical and horizontal distances that the hands can be moved away from the ankles and still have the capability of exerting a one-pound force.

After demonstrating the model results to various NASA personnel, it was also agreed that estimates of the horizontal and vertical work envelope dimensions for persons positioned in maximum force producing configurations would be helpful to equipment designers. To accomplish this, certain suit and body

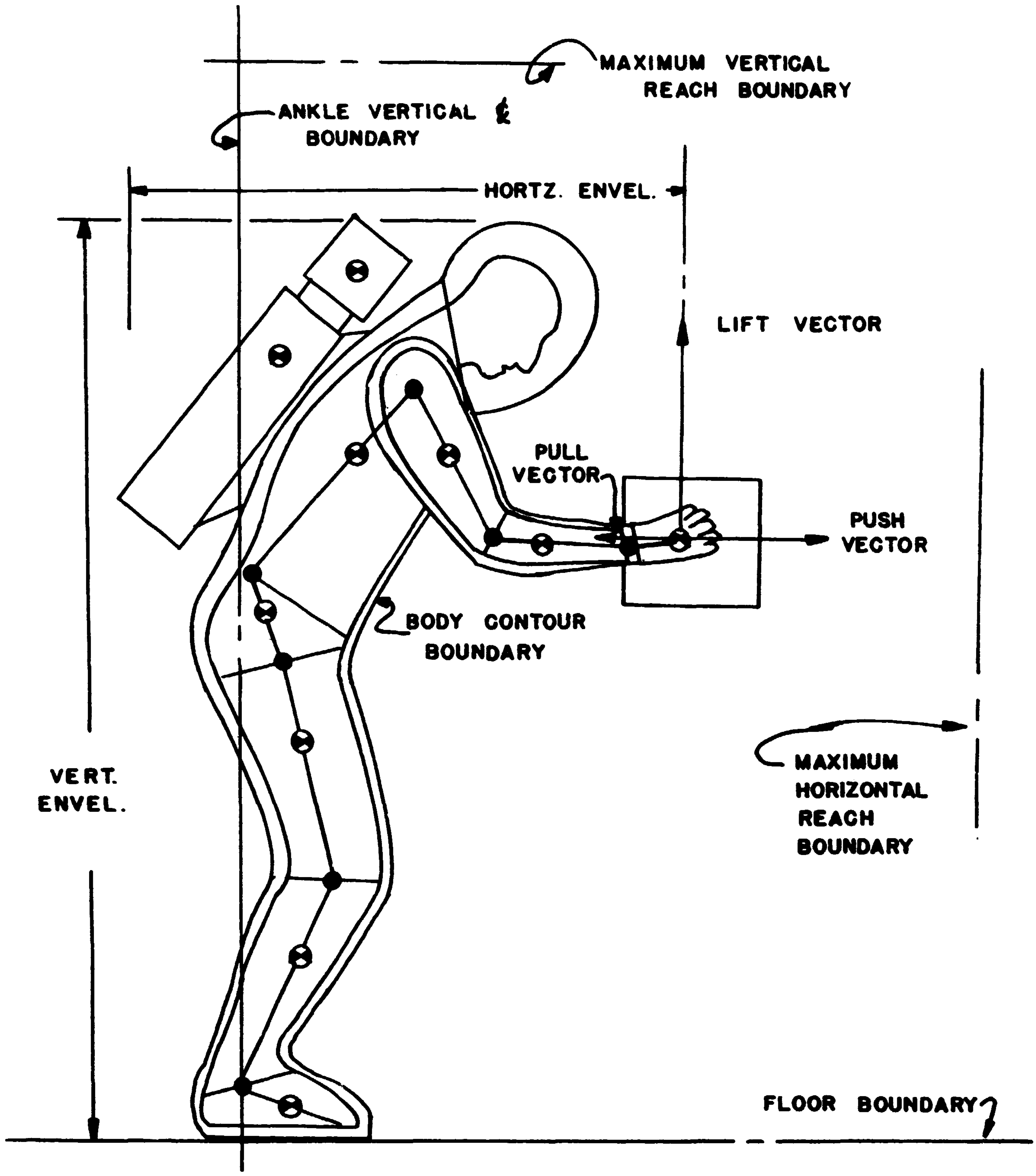

FIGURE I. LINKAGE REPRESENTATION OF MAN, INITIAL SIMULATION BOUNDARIES, AND WORK ENVELOPE DIMENSIONS segment areas were defined from the literature. These were then added to the linkage representation, thus providing a means to generate the work envelope predictions displayed in Figure 1.

Order of Reporting

The sections comprising the remainder of the report briefly contain the following information:

Section II describes the development of the computerized biomechanical model used in the simulations. Earlier validations are briefly described, followed by a detailed presentation of the input data used for the specific simulations.

Section III is a result section which graphically displays the predicted two-handed strengths for shirt sleeved activities as a function of hand positions, population size and strength, and gravity conditions. A summary of some general factors affecting shirt sleeved strength capabilities concludes the section.

Section IV is a result section following the format of Section III, except that it presents the two-handed force capabilities with an inflated A7L space suit and the PLSS and OPS backpacks.

Section V is a summary of the more general effects found from the two-handed force predictions. Limitations and possible extensions of the results are discussed.

II. The Development of the Biomechanical Strength Model

When a person performs a physical act, his muscles "pull" across the various bone articulations to create the forces necessary to counteract any external loads which may be acting on the body. One major result of either muscle or external forces acting at the various bone articulations is a rotational moment or torque, the magnitude and direction of which indicates the tendency of the bone to rotate about the articulation, as depicted in the text by Williams and Lissner (1962).

Based on this concept (i.e., that skeletal muscles produce torques at the various articulations of the body), it was hypothesized in earlier research that if a person's strength was ascertained by isometric tests in terms of his maximum torque producing capability at each of the major articulations, the resulting values provided limits as to the amount of hand force that a person (or specified group of people) could exert in various physical activities. This required that the torque limits provided by the controlled set of strength tests be compared to the torques produced at the same articulations by the body weight and hand forces developed during the performance of a physical activity. Thus, for any designated position of the body during a task, the relative utilization of the muscle strength capability at the various articulations of the body could be predicted. It has been found in subsequent use of this knowledge that better decisions regarding such alternatives as: 1) changes in work methods so that no one muscle group is overburdened while another is only slightly involved in the task, and 2) the need for mechanical work assistors (or changes in tools or workplace layout) have been possible.

Articulation torques due to a physical activity. The biomechanical model considers the body to be composed of a series of eight solid links as depicted earlier in Figure 1, (page 9). These links are the feet, lower legs, upper legs, pelvis, trunk (including the neck and head), upper arms, lower arms, and hands. The computational techniques of this model and other similar models have been described previously in detail by Chaffin, et. al. (1969 and 1970), Plagenhoef (1963), Pearson (1963), and Williams and Lissner (1962), and in the interest of conserving space, are herein only briefly summarized.

The mass of each link in the model is based on the segment-mass/body-mass ratios presented by Contini and Drillis (1963). The distribution of the mass within each link is based on the data of Dempster (1955). The link lengths can be established from over-the-body measurements, using the reference landmarks described by Dempster (1955). Specifically, the body measurements needed as input data are: body height, body weight, center-of-gravity of the hand to wrist distance, lower arm length, lower leg length, foot length, and elbow height when standing. Using these, the link lengths (i.e., the straight line distances between the articulation points-of-rotation) are estimated from the prediction equations developed by Dempster (1964). Because many of the specific dimensions needed for the model were not available for the Astronaut Corps, they were estimated based on the distribution of the astronauts' stature using the technique described by Dempster (1967). Table I describes the size data used in the simulations.

If the simulated person was wearing a space suit with backpack (EMU mode), additional masses were located on the body. The space suit mass was assumed to be distributed in the same proportions as the body mass, and added a total of 63 pounds to the man's weight. The PLSS and OPS mass centers-of-gravity were located from data obtained from the MSC-EVA Branch. The PLSS mass C.G. location was considered to be 12.45 inches vertical and 9.67 inches posterior to the hip joint, assuming an erect trunk. The OPS mass C.G. location was 26.8 inches vertical and 9.83 inches posterior to the hip joint. The PLSS added 93 pounds and the OPS added 40.89 pounds to the total 1.0 g. weight. Both the PLSS and OPS masses were assumed to move as a function of the trunk position.

Two additional sets of input data are required to develop a prediction as to the torques caused at each major body articulation by a physical activity. First, any external force that may be exerted on the hands is either measured for a specific activity of interest, or it is systematically increased in magnitude as a vector acting at the center-of-gravity of the hands. Figure 1 on page 9, depicts the three hand force vector directions used in the

Table I

Input Anthropometric Size Data

Dimensions*	Units	Means	Std. Dev.	Source
Weight (nude)	pounds	166	15	1
Stature (std. relaxed)	inches	69.8	1.9	1
Lower Arm Length	inches	10.2	0.4	2
Wrist-to-hand	inches	3.8	0.3	2
Lower Leg Length	inches	16.4	0.9	2
Foot Length	inches	9.2	1.1	1
Std. Elbow Height	inches	44.4	1.7	2

*Dimensions conformed to definitions stated by Dempster (1955).

Reference Source:

1. Distributions were developed from unpublished astronaut anthropometry, with assistance of NASA-MSC, Human Factors Group, EVA Branch.

2. Distributions were estimated based on astronaut statures using the technique proposed by Dempster and Gaughran, 1967. A comparison of these values with 50 males selected randomly and measured for the dimensions showed less than a 1.5% error in the stature-based estimates.

project. Second, the hand position relative to the ankles is determined from input values that describe both the maximum vertical and horizontal reach boundaries,[1] and the incremental distances within which the hands are to be systematically moved. For the force simulations required in this project, the hands were moved in varying increments of between two and ten inches within the rectangular area depicted in Figure 1. It should be noted that the hands were not allowed to assume a position which would result in an object striking the front of the body. In other words, if the body configuration in a simulation was such that the legs, torso, or head was between the hands, the particular body configuration was disallowed and another body configuration was generated, as described later in this section.

In summary, articulation torques caused by the body weight, EMU weight, and any load acting on the hands were computed based on the preceding, and using biomechanical concepts described in detail by others, such as Plagenhoef (1963), Dempster (1955), Pearson, et. al. (1963), and Chaffin (1969 & 1970).

Estimating the Articulation Torque Limits. As described in Section I, voluntary muscle strengths can be converted to provide maximum values for articulation torques. This requires that the strengths be obtained in a specific manner. Body position, type of contraction, and anthropometric parameters are major variables

[1] These boundaries are only selected to provide limits for the hand movement interations. The actual reach capabilities are estimated by the program iterating the body configurations through the ranges-of-motion of each joint to determine where closed link systems exist.

that need to be controlled.

Because strength data obtained in a systematic fashion is not presently available on the astronauts, the required model strength inputs needed to be estimated from other population strength data. The major strength data used were obtained with the cooperation of 50 males selected randomly from an electronics assembly industry.[1] These were compared to other published data and augmented by other data, as summarized in Table II. It is believed that these are the best available estimates of the specific muscle strengths needed as inputs to the biomechanical model.

Because a muscle's strength is a function of its length, and because the mechanical advantage of different muscles acting about each articulation have been shown to change with the angle of the segments forming the joint, it was deemed necessary to include a scheme for extrapolating the strength data obtained in the specific test positions to be applicable through-out the range-of-motion of the various articulations. This was accomplished by deriving a set of proportionality constants based on the strength variation curves for different angulations, as depicted by Clarke (1966), Morgan, et al. (1963), and Elkins, et al. (1951). Appendix A depicts these average effects. As an example of this technique: if a person was found to produce a maximum voluntary elbo flexion torque of 435 inch-pounds at the elbow test position of 90°, he would have a predicted torque limit of 82 percent of this value

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[1] The strength values were obtained as described by Chaffin and Baker (1970) from production employees at the Western Electric Works, Kansas City, Mo.

Table II

Input Strength Data

Muscle Action	Included Angles	Torque (inch-pounds) Means	Std. Dev.	Reference Sources
Elbow Flexion*	90°	616	126.7	Chaffin et al(1970)
Elbow Extension	90°	374	69	Singh et al(1966 & 68)
Shoulder Flexion*	+30°	744	159	Chaffin et al(1970)
Shoulder Extension	+30°	738	153	Williams et al(1959)
Hip Flexion	90°	1359	232	Elkins et al(1951)
Hip Extension*	90°	2989	941	Chaffin et al(1970)
Knee Flexion	90°	456	71	Clarke et al(1966)
Knee Extension*	120°	1614	419	Chaffin et al(1970)
Plantar Flexion*	90°	1970	600	Chaffin et al(1970)

* The major muscle strengths were obtained in a manner described by Chaffin and Baker (1970) with the cooperation of 50 male employees of the Western Electric Company, Kansas City Works. These employees matched-out to be one inch shorter than the astronauts, but of the same average weight.

(i.e., 357 inch-pounds) if the elbow was flexed to 60° during a particular physical activity. This procedure of "weighting" the maximum torques from the strength tester is repeated in the model for all six articulations, thereby providing a set of nine torque limits that reflect both individual muscle strength variations based on the test data, as well as the average effect of body position on a person's strength.

Since an inflated space suit provides some resistance to both movement and maintenance of certain body positions, the proportionality constants that were developed to modify a shirt-sleeved individual were corrected for the torque effects of the A7L fully inflated suit.[1] The resulting changes in an average male's predicted strengths are depicted in Appendix A. In some specific muscle actions, the inflated suit reduces the range-of-motion at articulations. This effect is depicted on the graphs of Appendix A by the magnitude of the angle spanned by the "suited" torque functions.

<u>In summary</u>, muscle isometric strength data were obtained to serve as limits to the articulation torques resulting from external loads during a physical activity. The major strengths were from studies by these investigators, and represent the average strengths exerted for four seconds by a group of males of similar age and weight, but of slightly smaller stature that the astronauts. Other published studies which controlled body positions were also

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[1]Articulation torques on the A7L fully inflated suit were derived from data supplied by MSC personnel, EVA Branch.

used. It is not as clear how other variables were controlled in these experiments, but a check of some of the values against these investigators' unpublished data confirms that they are similar in magnitude.

Unfortunately, systematic evaluation of muscle strength in general has not been done. The data used for the simulations is believed to provide reasonable strength estimates. It is hoped that future attention will be given to this data deficiency for not only the astronauts, but also other strata of the population.

The stresses at the lumbosacral joint as a limit to physical capacity. The lumbosacral disc area was selected for inclusion of a separate limitation to the physical strength due to the high incidence (i.e., 40-50 percent) of disc herniations incurred at this segmental level during back lifting activities. In essence, this additional evaluation estimates the compresstion at the lumbosacral disc by treating the trunk as two separate solid links (i.e., the pelvis and the spine) rather than only one link, and then computing the torques and forces resulting at the lumbosacral articulation of these two links by assuming normal values for the rotation and muscle actions of the back and abdomen during back lifts. A complete description of the biomechanical model of the spine is presented by Chaffin (1969). The maximum compression forces were derived from both published values, Troup (1969), and from analysis of back lifting activities, Chaffin (1969).

Body balance as a limit to physical capacity. A standing person maintains his body balance by selecting body positions which have the resultant rotational torque at the ankle (caused by the body weight or any other external forces acting on the body), counteracted by the equal in magnitude but opposite in direction reactive rotational torques, caused by the ground pushing against either the ball or posterior aspect of the heel of the foot. If the foot flexion or extension muscle strength is sufficient, then the ground force acting on the foot is simply equal to the sum of the whole body weight, the weight of any object attached to the body, and the downward vertical component of any other force acting on the hands. Thus the counteracting reactive torque at the ankle is the product of the ground force counteracting the body weight and horizontal distance between the ankle and either: 1) the posterior aspect of the foot when tending to fall over backward, or 2) the ball of the foot if tending to fall over forward. Since these quantities are independent of body position, the maximum reactive ankle torque provides a specific limit to which the resultant ankle torques, caused by the body being in various positions, can be compared. If a particular body position during an activity causes an ankle resultant torque to be greater than the maximum ankle reactive torque, then the person is said to be out of balance.

Program Procedure. The preceding has described three separate limits that are included in the biomechanical model. The first limit is provided by the muscle strength of a statistically defined proportion of the population. The procedure for using this limit to predict the two-handed force capability, given a particular required hand position in respect to the ankle, is briefly as follows: the computer model first assumes a feasible body position, i.e., one that does not violate any one articulation voluntary ranges-of-motion and still allows the person to place his hands in the position of interest. The model then performs a binary search to determine the force added to the hands which will cause one of the articulation torques to equal the articulation muscle strength limiting torques. When any of the maximum voluntary articulation torques has been exceeded by one of the computed articulation task torques, the program stores: 1) the force at the hands that created that particular articulation task torque, 2) the predicted maximum voluntary articulation torques, and 3) the body configuration generating the hand force.

The second limit to the physical force capability is then introduced—the lumbosacral compression limit. The procedure is similar to the above. For the given body configuration, the hand force which causes the predicted compression limit to be equalled is determined by a binary search. The maximum value of the hand force is then stored.

The smallest of the three stored hand forces is taken to be the maximum hand force capability for the assumed body configuration. The model then discretely changes the body to other feasible positions by successively adding incremental degrees to each body articulation.[1] The maximum force capability for each body configuration is computed and stored. The largest of these stored hand forces and its associated body position is then printed-out, thereby producing: 1) a prediction of the maximum two-handed force that a person can exert when his hands are in a particular position, 2) an indication of whether a skeletal muscle group, back strength or body balance is limiting the person's hand force capability, and 3) the body configuration required to produce the maximum hand force. (For this report, gross body configurations are depicted by a set of "standard positions" shown in Appendix C.)

Prediction of Work Envelope. An additional subroutine is utilized to predict the horizontal and vertical dimensions of the space occupied by an individual (as depicted in Figure 1, page 9), when in his maximum force producing position. This subroutine uses published over-the-body dimensions of a person in both shirt-sleeves and when in a fully inflated suit, as developed by Bell, 1968, and Damon, Stoudt, McFarland, 1966.

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[1]An input card states the magnitude of the changes in body position.

The dimensions for the largest 5% of the male population, as defined in the following subsection, are printed-out for design reference. Appendix C depicts these work envelope dimensions for many of the conditions simulated and discussed in Sections III and IV of the report.

Validity of existing model. The proposed biomechanical model has been validated using an industrial working population, Chaffin and Baker, 1970. The validation was accomplished by selecting individuals with widely varying strength characteristics, as depicted earlier in Table II. The people were then asked to exert maximum hand forces that required whole-body efforts; primarily, attempting to lift heavy objects in different body positions. The hand forces were measured, along with the body positions chosen by the people. When the model was used to predict their maximum hand force capability, the resulting predictions were found to be unbiased (i.e., did not over or under predict the group's strength), and were well-correlated with the actual ($r = 0.82$).

As mentioned earlier, the muscle strength test is highly dependent upon the motivation of the subjects. It is therefore hypothesized that because of consistently higher motivation and better cooperation from the astronauts (than could be assumed probable in the industrial sample), the model could result in even better physical force predictions. This fact would become very important if in the future it were desired to test each astronaut and evaluate his particular physical capabilities during various projected alternative IVA and EVA requirements. The fact that the hand force predictions from the model are unbiased simply means that the model can be used at present to evaluate the methods and design of the hardware used by a stated group of people.

Simulation Input Data. Five input variables were systematically varied in this project to determine their effects on two-handed force capabilities. Four of these are considered "physical design variables," in that they are specified by the designer in specific quantitative language. These are listed below:

* Hand placement. This variable is designated by giving the horizontal and vertical coordinates of the hand center-of-gravity (approximate palm center) relative to the ankles. Since this is obviously a major design variable, it was systematically varied for each level of the following variables to provide a force capability assessment for the complete reach capability area located anterior to a line running vertically through the ankles, as depicted earlier in Figure 1, page 9.
* Hand Force Direction. This variable designates that either a lift, push, or pull action is being simulated (see Figure 1, page 9). All three of these conditions were simulated. (Other hand force directions can be studied than the orthagonal set used in this project.)

* Gravity. Three levels of this variable were chosen to depict the normal earth environment (1.0 g.), the lunar environment (0.2 g.), and a spinning platform of slightly reduced gravity environment (0.7 g.).
* Clothing. Two conditions were simulated: "Shirt-sleeved," which referred to an unencumbered person (i.e., no significant weight or physical constraint due to the clothing), and "Suited," which referred to the A7L space suit with backpack (EMU mode) in a pressurized (3.75 psi above atmosphere) condition.

The fifth variable considered in the simulations is the size and strength of the population. This variable is not a single-dimensional factor. The data comprising the complexity of the variable is summarized in the earlier Tables I and II. As written at present, the biomechanical model requires sixteen different body dimensions to describe the anthropometry (size and strength) of an individual. The values of each one of these dimensions could be systematically varied to estimate the effect of each one on a person's predicted hand force capability. This would be worthwhile only if one were interested in selecting specific individuals, based on their anthropometry, to perform designated activities.

As mentioned earlier, only a few of the astronaut body size dimensions were available, and no strength data was obtainable. Another consideration was that for design of hardware and work methods, it would probably be best at present to present the hand force predictions as a function of a defined proportion of the population (e.g., 5, 50, and 95 percents). This would then allow the designer to examine his specifications to determine the "general" effects on the potential group or person, thus not delaying advanced design concepts until specific individuals are designated for a mission. It is also the belief of these investigators that too much "personalization" of the model input data could result in poor design, since absolute designations as to who would be performing each task in a mission is not feasible.

Based on this reasoning, the following procedure has been followed to develop estimates of the 5, 50, and 95% of the population that would be capable of exerting the forces predicted by the model for each of the previous four "physical design variables." First, it must be recognized that each of the anthropometric dimensions presented earlier in Tables I and II are not independent of each other, nor, on the other hand, are they completely correlated. Table III on the following page presents the cross-correlations between twelve of the major dimensions. The effect of this situation is that any statement as to what proportion of the population can perform some task must include consideration of the relative dependencies of various anthropometric dimensions. For instance, the statement that 50% of the population would be larger than all of the means of the dimensions listed in Table I would be true only if all of

	Dimensions:	SIZE							STRENGTHS				
		Body Weight	Height	Lower Arm	Wrist to Hand C.G.	Lower Leg	Foot	Elbow Ht.	Ankle Ext.	Knee Ext.	Hip Ext.	Shoulder Flex.	Elbow Flex.
SIZE	Body Weight	1.00											
	Height	.28	1.00										
	Lower Arm	.36	.32	1.00									
	Wrist to Hand CG.	.30	.29	.06	1.00								
	Lower Leg	.50	.60	.76	.25	1.00							
	Foot	.37	.50	.64	.32	.73	1.00						
	Elbow Ht.	.50	.71	.48	.29	.75	.61	1.00					
STRENGTHS	Ankle Ext.	.29	.13	.05	.40	-.00	.18	.14	1.00				
	Knee Ext.	.06	-.20	.11	.11	-.02	-.14	-.17	.41	1.00			
	Hip Ext.	.13	-.10	-.00	.22	-.13	-.22	-.09	.42	.72	1.00		
	Shoulder Flex.	.37	-.14	.01	.28	.05	-.01	.00	.52	.57	.53	1.00	
	Elbow Flex.	.36	.02	.21	.18	.22	-.05	.12	.40	.61	.55	.61	1.00

Data values in Tables I and II from study by Chaffin and Baker of 50 Western Electric employees.

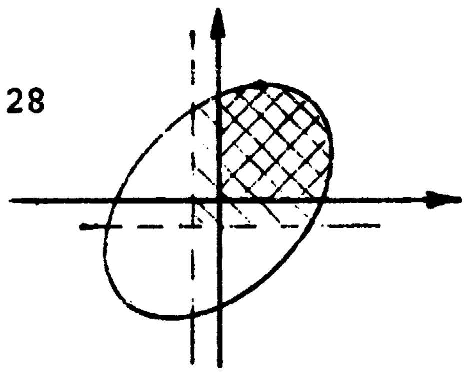
Table III

Cross-Correlation of Anthropometric Dimensions the dimensions were uniquely correlated. Since this is not true, as displayed in Table III, less than 50% of the population would be greater in size than all of the means. The same reasoning applies to the strength dimensions.

This then requires that each of the distributions of the dimensions presented in Tables I and II be "shifted" in value to provide a set of input anthropometric dimensions to the program which, when considered in total, better represent a stated proportion of the population. The estimating of the amount of change required for the distributions is illustrated in the following for two dimensions (height and weight):

The correlation between height and weight is depicted below: W-weight (pounds)

r = 0.28



H-height (inches)

——— means of weight and height
------ percentile axes needed to encompass stated proportion of population in both dimensions.

proportion of population greater than both means.

stated proportion of population to be greater than both of the designated percentile axes including space bounded by means (for example 50% of population).

As can be seen by inspection, the percentile axes needed to assure that 50% of the population exceed both a specific weight and height must be shifted to be less than the means of either the weight or height. The problem then is to determine what magnitude of each dimension (stated as a percentile point of the standardized variate) must be chosen to assure that a desired proportion of the population is encompassed. This problem can be presented in probability statements:

$$Pr(H \geq X,\ W \geq X) = Pr(H \geq X)Pr(W \geq X/H \geq X) = 50\%$$

where X is the percentile point on each standard variate that assures that the proportion of the population desired (i.e., 50% in this case) exceeds the values of both dimensions. H and W are the standardized values of height and weight.

The conditional probability that the standardized weight variate W is greater or equal to the value of X, given that the standardized height variate H is greater than X is dependent on the correlation coefficient, which is 0.28 (from Table III) for our example. Referring to a set of bi-variate normal tables published by the National Bureau of Standards (Applied Mathematics Series, 55), results in X being estimated at -0.86, which assures that 50% of the population would exceed both dimensional values of 154 pounds and 68.2 inches.

To generate the input data for the biomechanical model, this procedure is repeated for each combination of dimensions in Table III to generate values of X that include consideration of all of the dimensional dependencies, and for 5, 50, and 95% of the population. In this general algorithm, the combination of dimensions chosen to develop the X estimates is based on any six out of the twelve dimensions needing to be exceeded by the given proportion of the population, rather than all twelve dimensions. The rationale for this is that when many body dimensions are mutually considered, they tend to diminish the joint space unrealistically for design purposes. This is because when one dimension is unproportionally greater than another for an individual, when he performs certain activities the larger dimension can compensate for the smaller dimension. In other words, the algorithm acknowledges that for given activities some body dimensions are more important than others, but because physical activities must be considered in general terms for a design algorithm, the specification of the body dimensions must allow for "general" compensating effects. Thus to hold to the rule that all dimensions must be exceeded by some proportion of the population is too rigorous, and would result in extremely conservative design parameters.[1]

[1]A complete description of this algorithm is being prepared by these investigators for publication.

Table IV on the following page summarizes the anthropometric values used as input to the biomechanical model.

Table IV

Biomechanical Model Input Data

Anthropometric Dimensions *	Proportion of Male Population greater than at least six of the following dimensions:		
	95% (small & weak)	50% (average)	5% (large & strong)
Weight (nude, pounds)	145.9	167.2	191.5
Stature (Std. relaxed, in.)	67.2	70.0	73.0
Lower arm length (inches)	9.7	10.2	10.9
Wrist-to-hand length (in.)	3.4	3.8	4.3
Lower leg length (In.)	15.2	16.5	17.9
Foot length (inches)	8.4	10.0	11.8
Standing elbow height (in.)	42.1	44.5	47.3
Torque (inch-pounds):			
Elbow Flexion	436.1	616.0	821.3
Elbow Extension	281.5	379.5	491.3
Shoulder Flexion	517.9	743.7	1001.3
Shoulder Extension	521.0	738.2	986.1
Hip Flexion	1029.1	1358.6	1734.4
Hip Extension	1652.7	2988.7	4512.8
Knee Flexion	354.9	455.7	570.7
Knee Extension	1019.6	1614.3	2292.8
Plantar Flexion	1118.5	1969.8	2941.0

*See Tables I and II for sources.

Section III

Results of Shirt-Sleeve Strength Predictions

This section presents the two-handed force capability predictions for an unencumbered male population. The force predictions are displayed in graphical form as a function of both the horizontal and vertical displacements of the hands in front of or above the ankles.

The order of reporting the force predictions is in three major subsections: the first for lifting, the second for pulling, and the last for pushing. Within each subsection, the graphs are divided into the three gravity conditions (1.0, 0.7, and 0.2 g's). For each gravity condition, a sequence of three graphs present the force predictions for 5%, 50%, and 95% of the male population (as defined by Table IV on the preceding page).

In addition to the graphs presented in this section, Appendix C displays a set of force predictions for specific vertical hand heights. The hand heights chosen for this presentation are depicted by horizontal section lines drawn across the equal hand force graphs in this section. The numbers at the end of these lines refer to the specific graphs found in Appendix C. The corresponding graphs in Appendix C are marked in the upper right hand corner with the same numbers. The graphs in Appendix C also display the work envelope dimensions and the gross body positions (with reference to a set of standard positions) required by a person who is exerting his maximal hand force.[1]

A summary section describes the major factors that affect the hand force of a shirt-sleeved individual. Implications regarding safety are also discussed in the summary at the end of the section.

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[1]Specific body positions are outputted from the program and can be obtained for specfic tasks upon request to the Engineering Human Performance Laboratory, Department of Industrial Engineering The University of Michigan, Ann Arbor, Michigan, 48105.

Shirt-Sleeved Two-Handed Force Predictions

during

Lifting

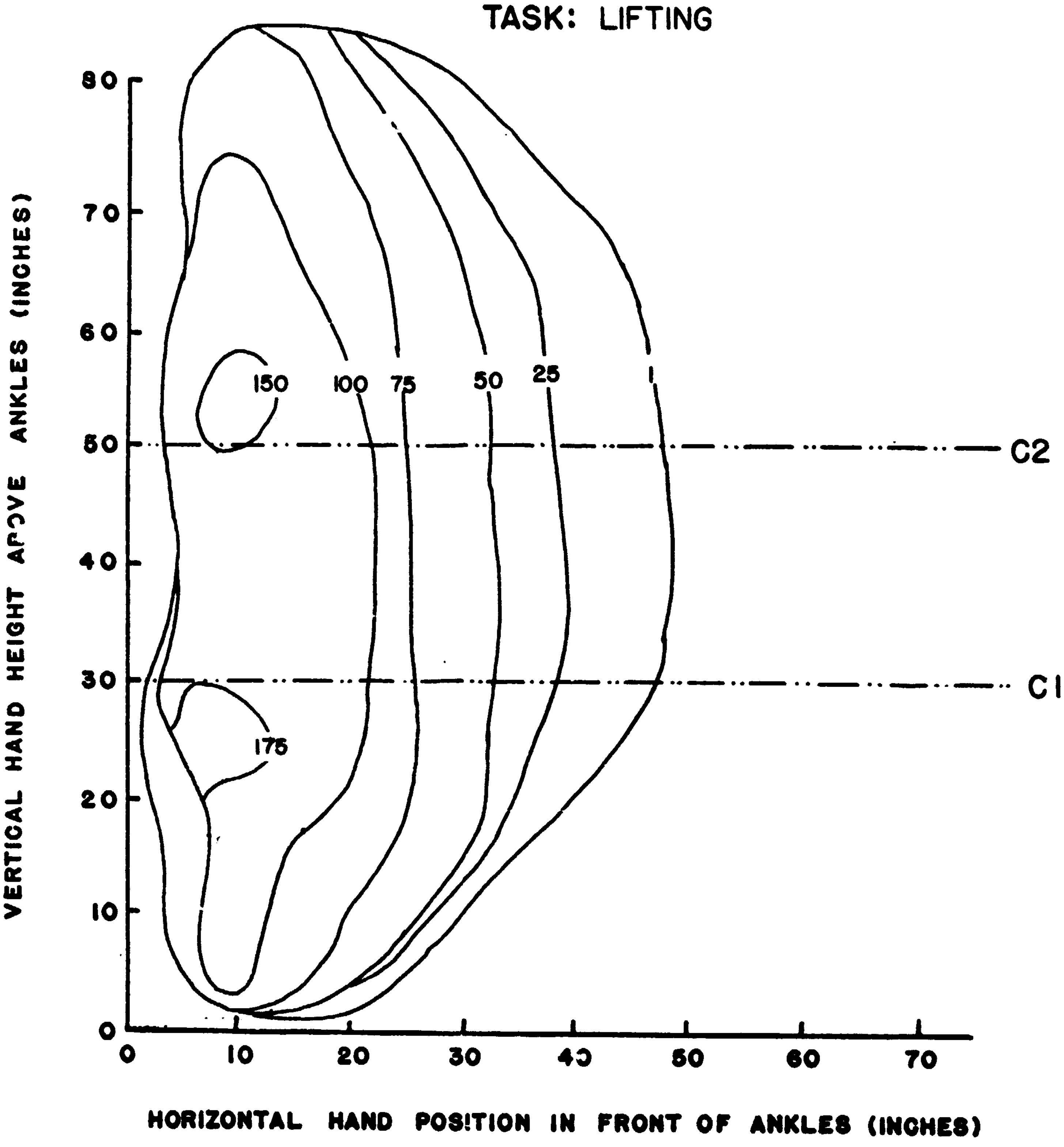
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 1.0 G

CLOTHING: SHIRTSLEEVED

TASK: LIFTING



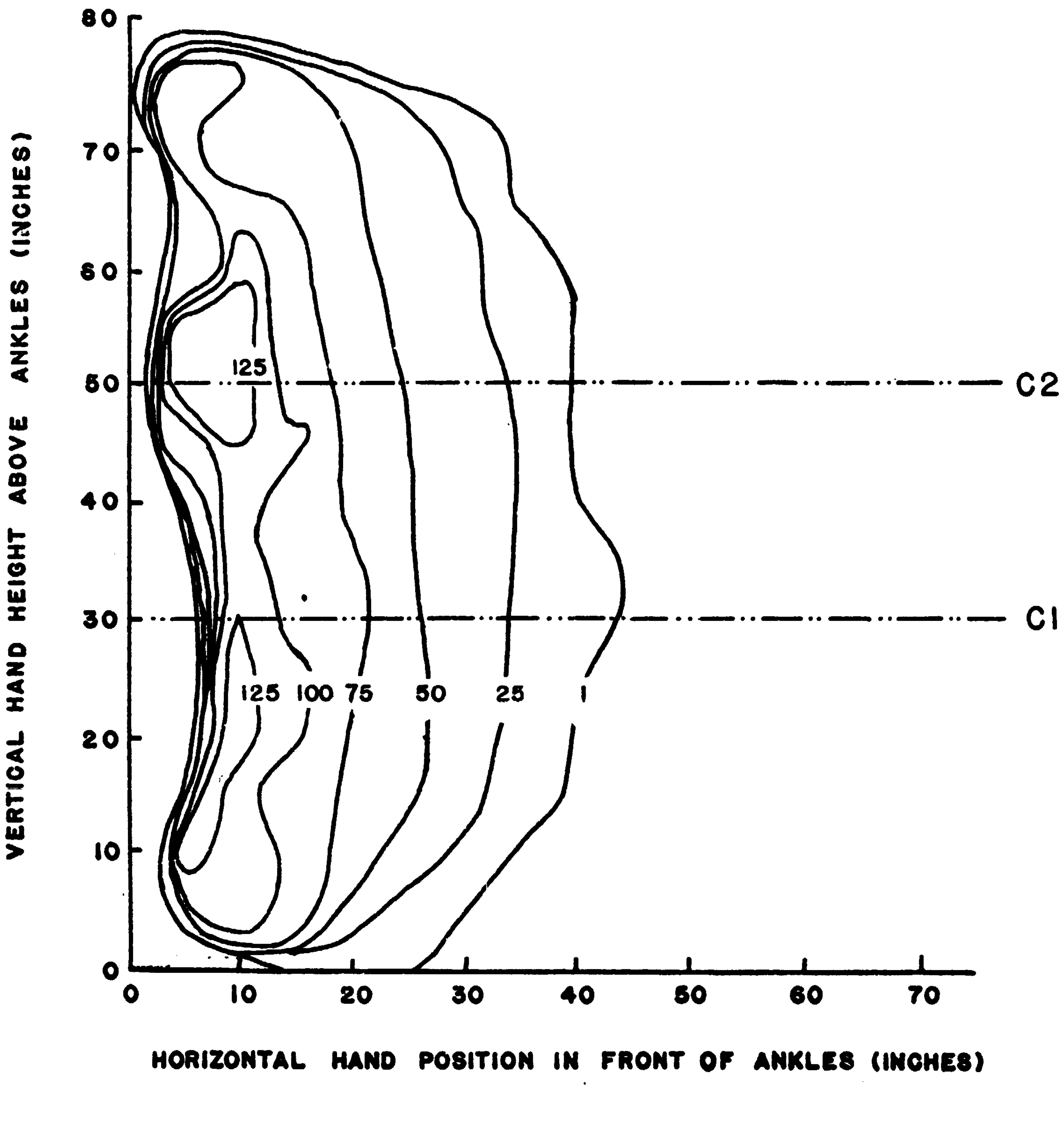
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 1.0 G

CLOTHING: SHIRTSLEEVED

TASK: LIFTING



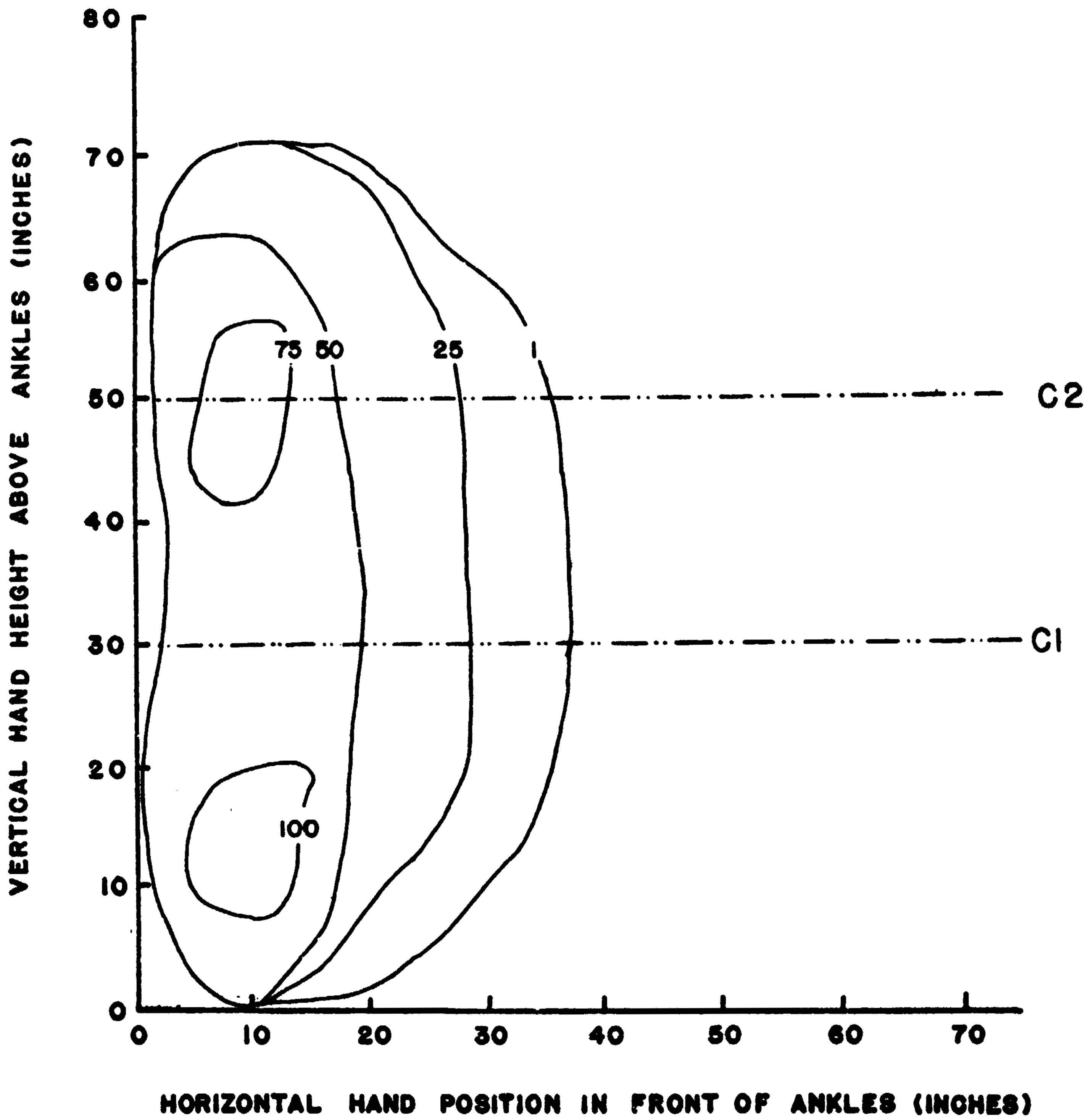
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95 %

GRAVITY: 1.0 G

CLOTHING: SHIRTSLEEVED

TASK: LIFTING



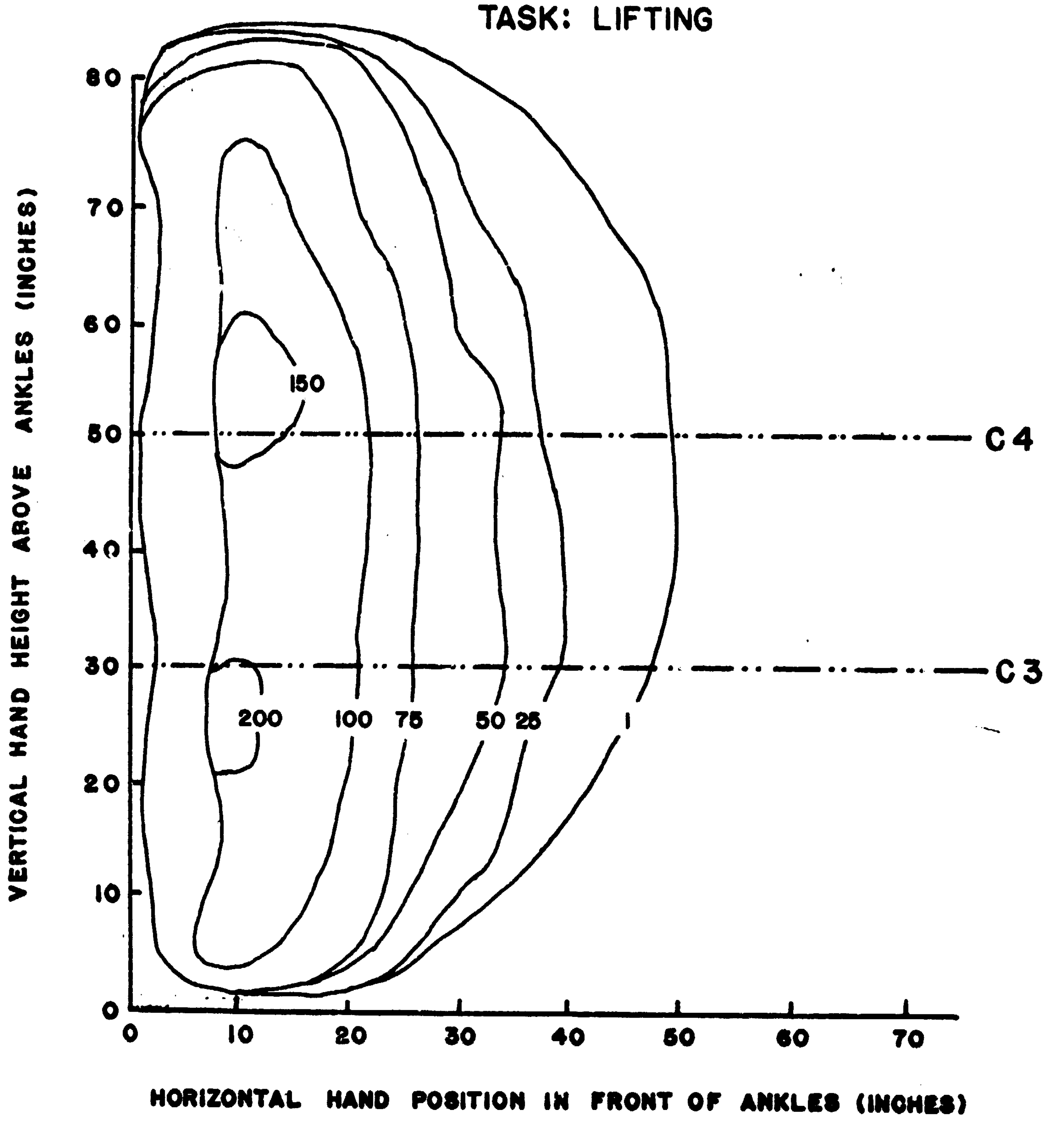
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 0.7 G

CLOTHING: SHIRTSLEEVED

TASK: LIFTING



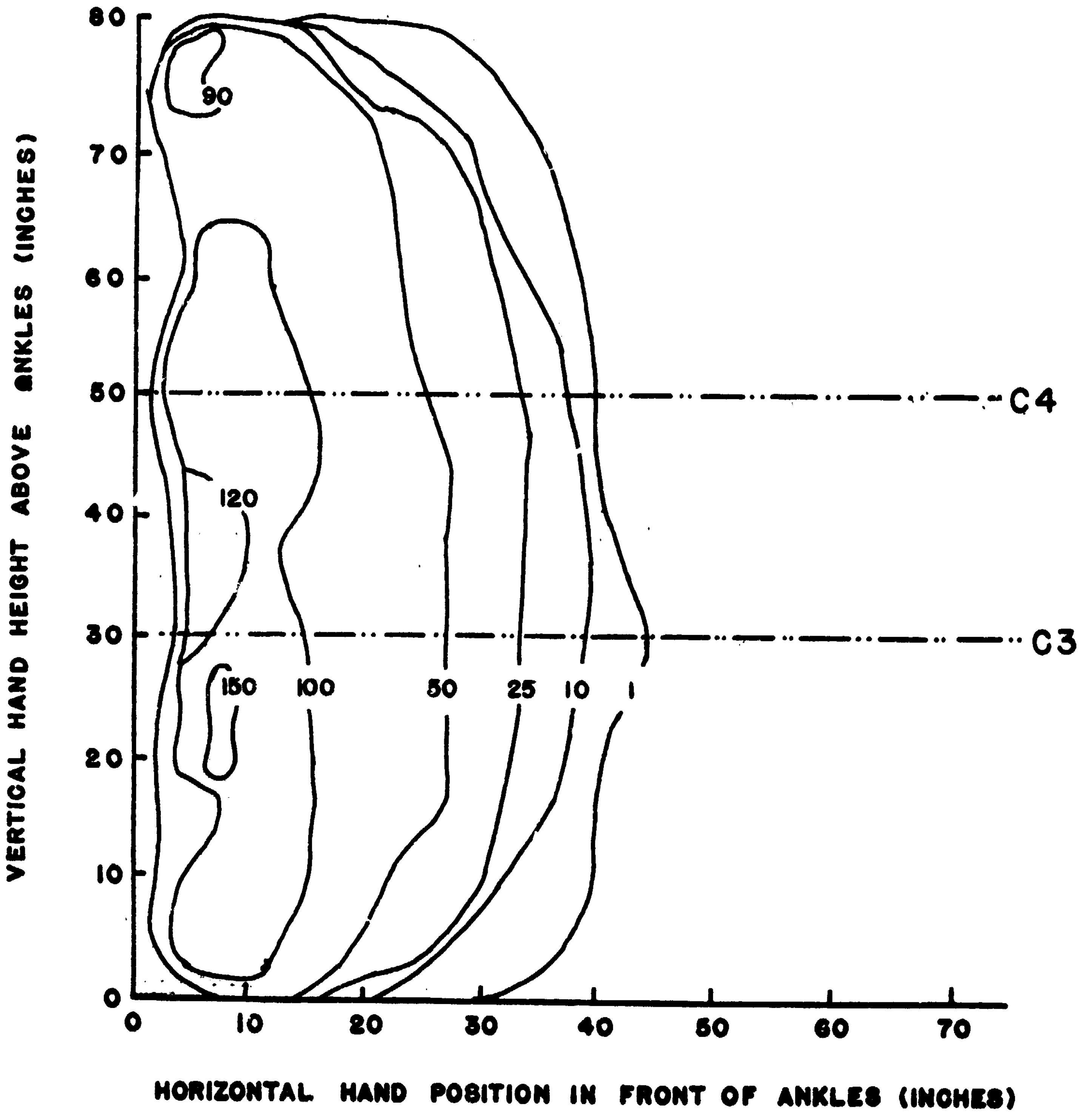
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 0.7 G

CLOTHING: SHIRTSLEEVED

TASK: LIFTING



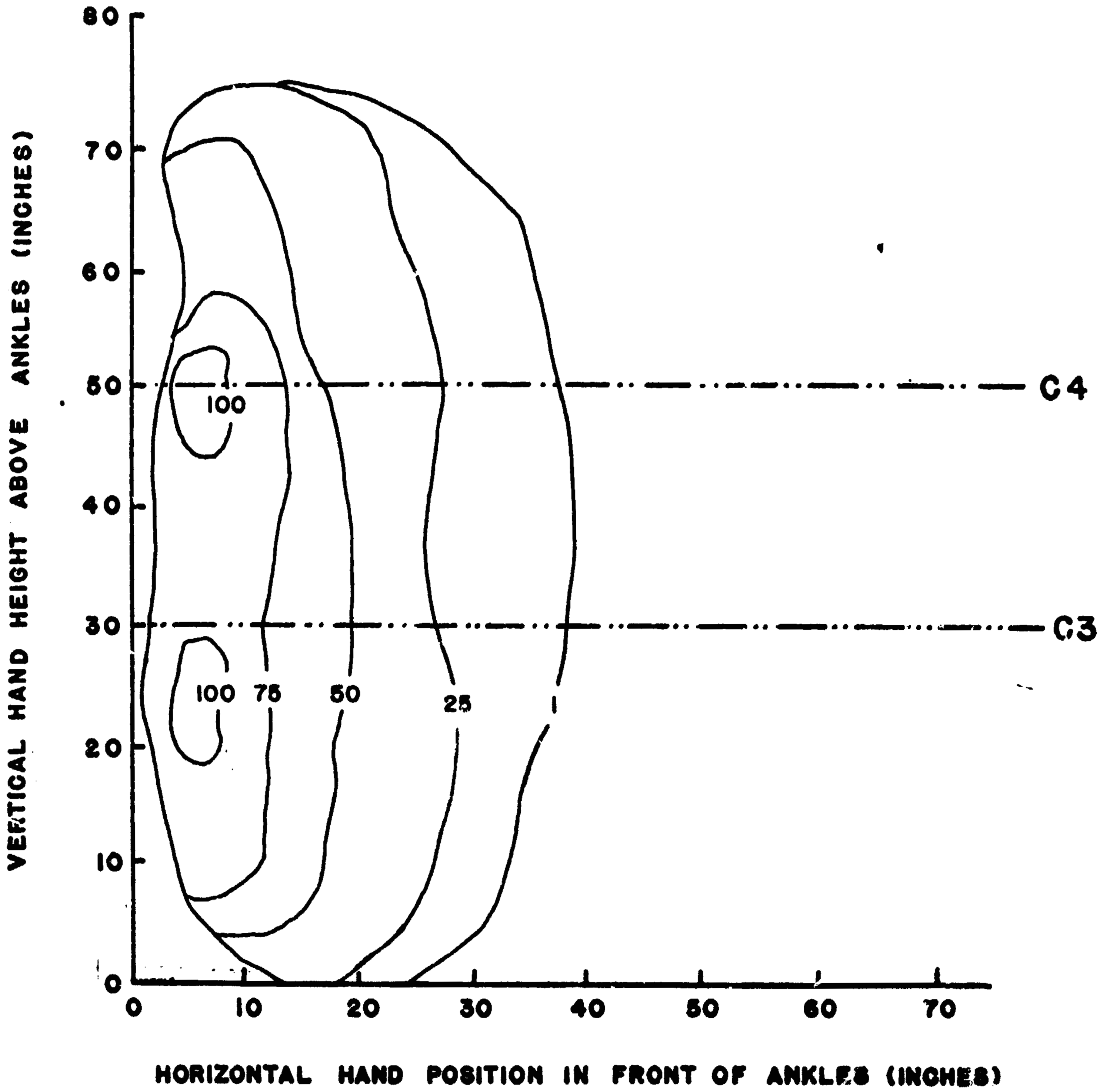
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

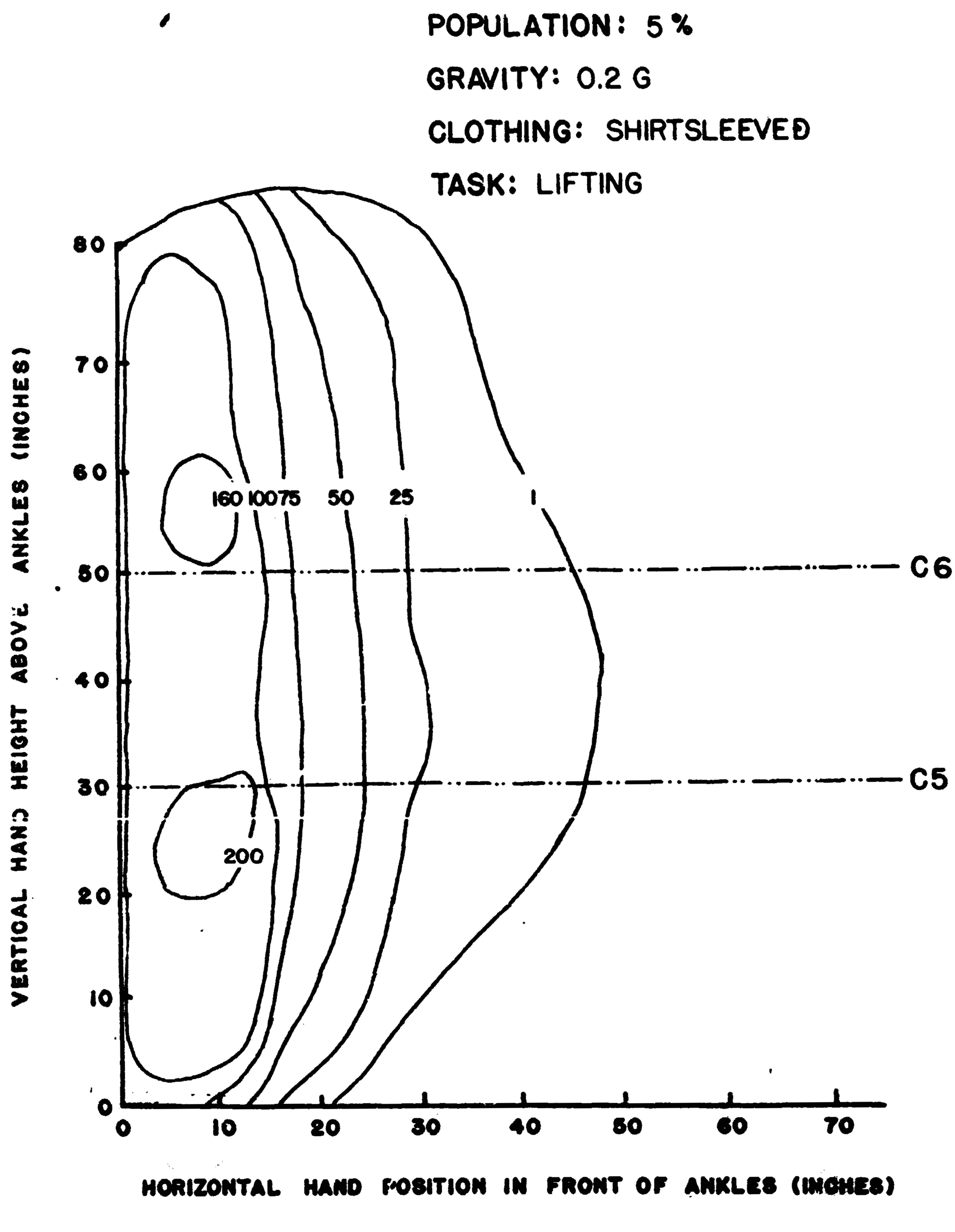
GRAVITY: 0.7G

CLOTHING: SHIRTSLEEVED

TASK: LIFTING



PREDICTED EQUAL HAND FORCE CAPABILITIES



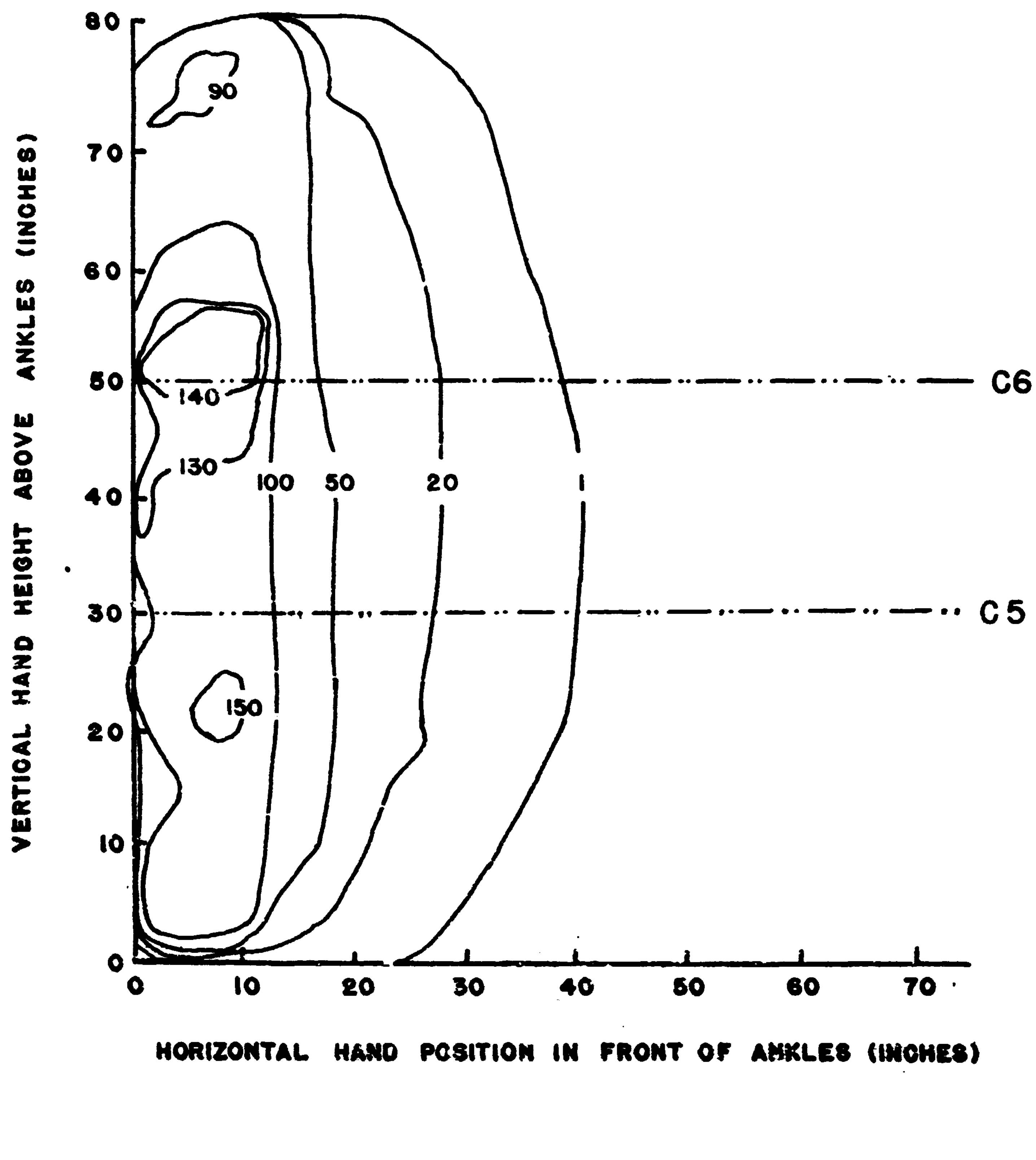
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 0.2 G

CLOTHING: SHIRTSLEEVED

TASK: LIFTING



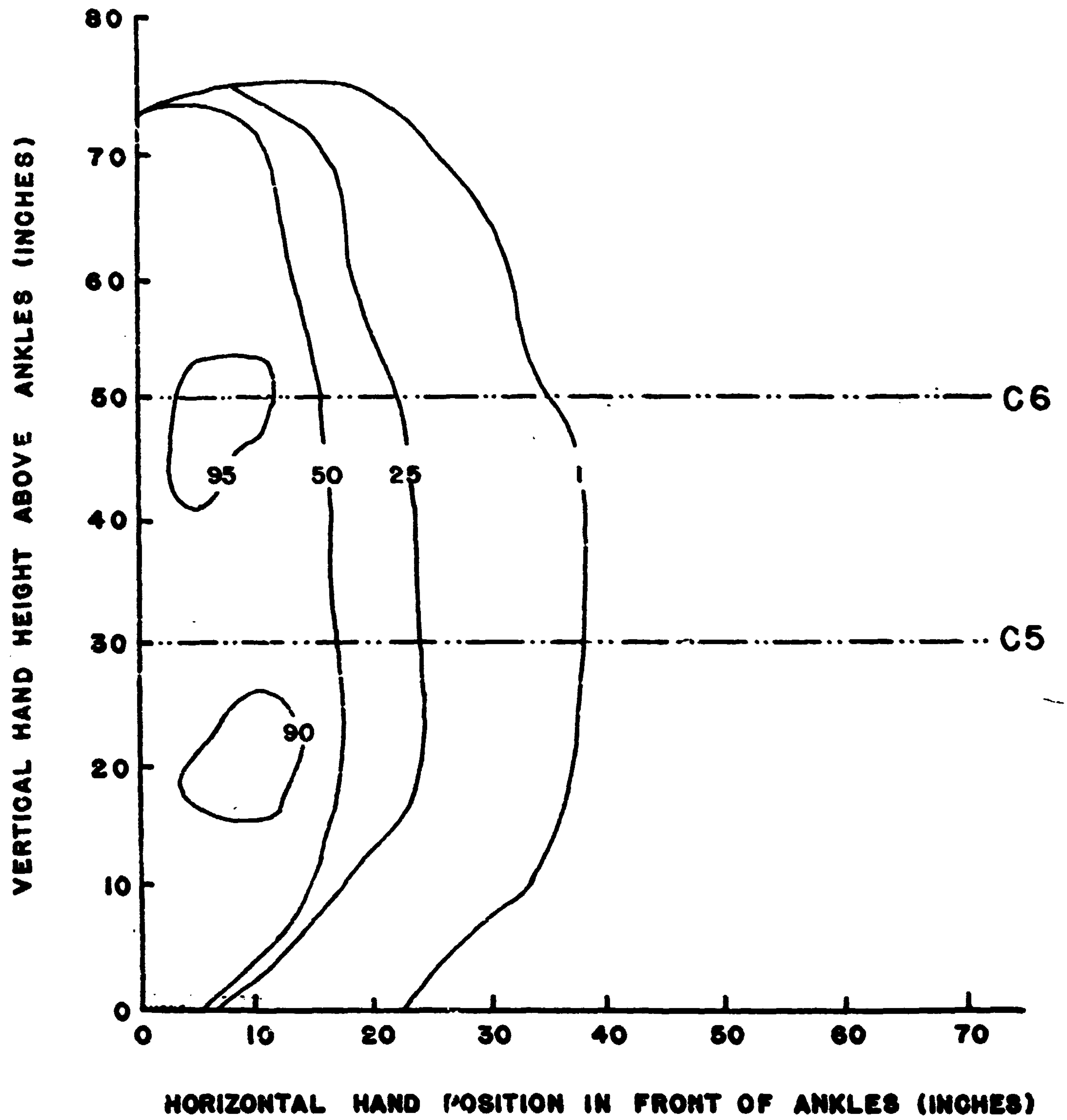
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 0.2 G

CLOTHING: SHIRTSLEEVED

TASK: LIFTING



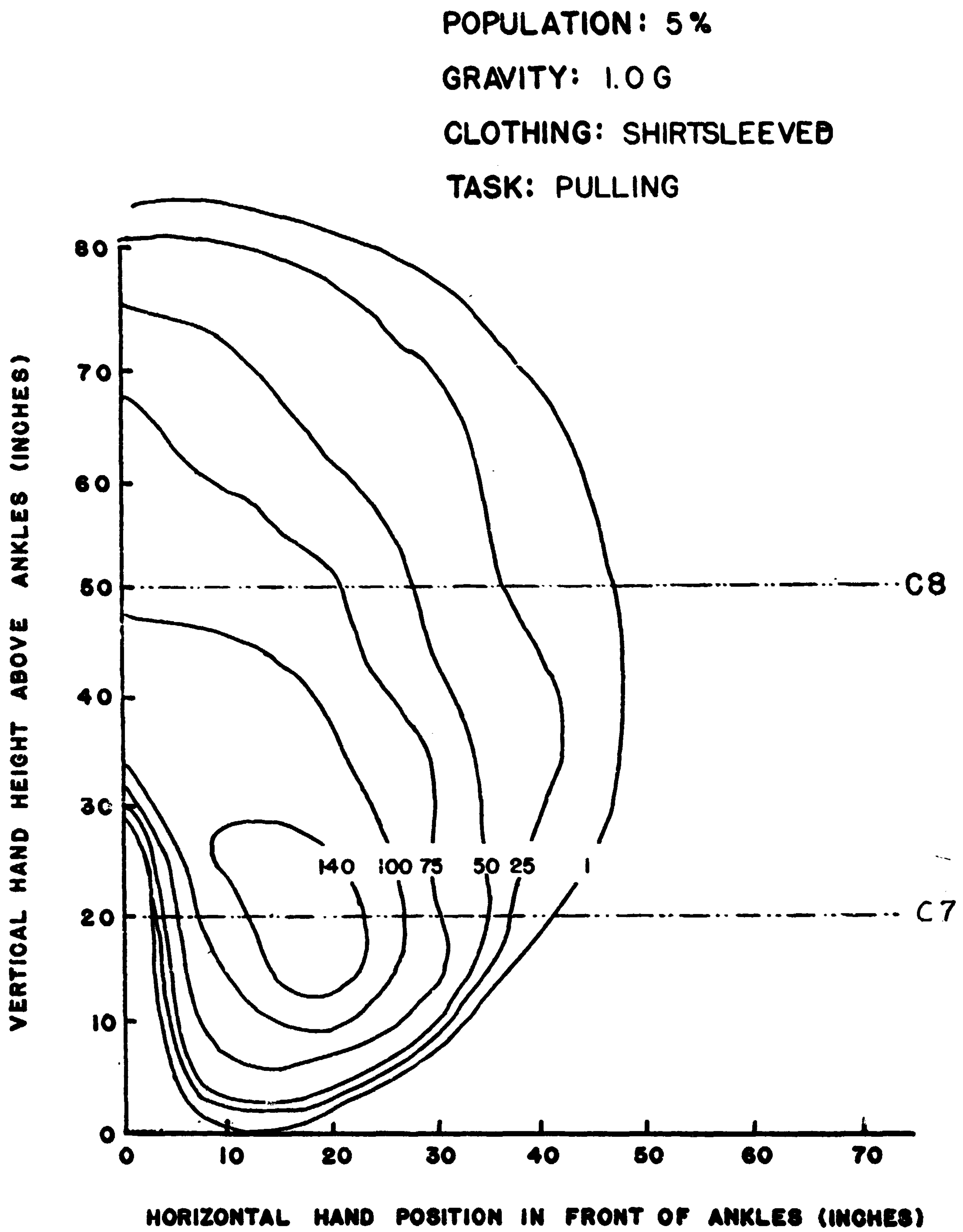
Shirt-Sleeved Two-Handed Force Predictions

during

Pulling

Conditions: | | Page:

PREDICTED EQUAL HAND FORCE CAPABILITIES



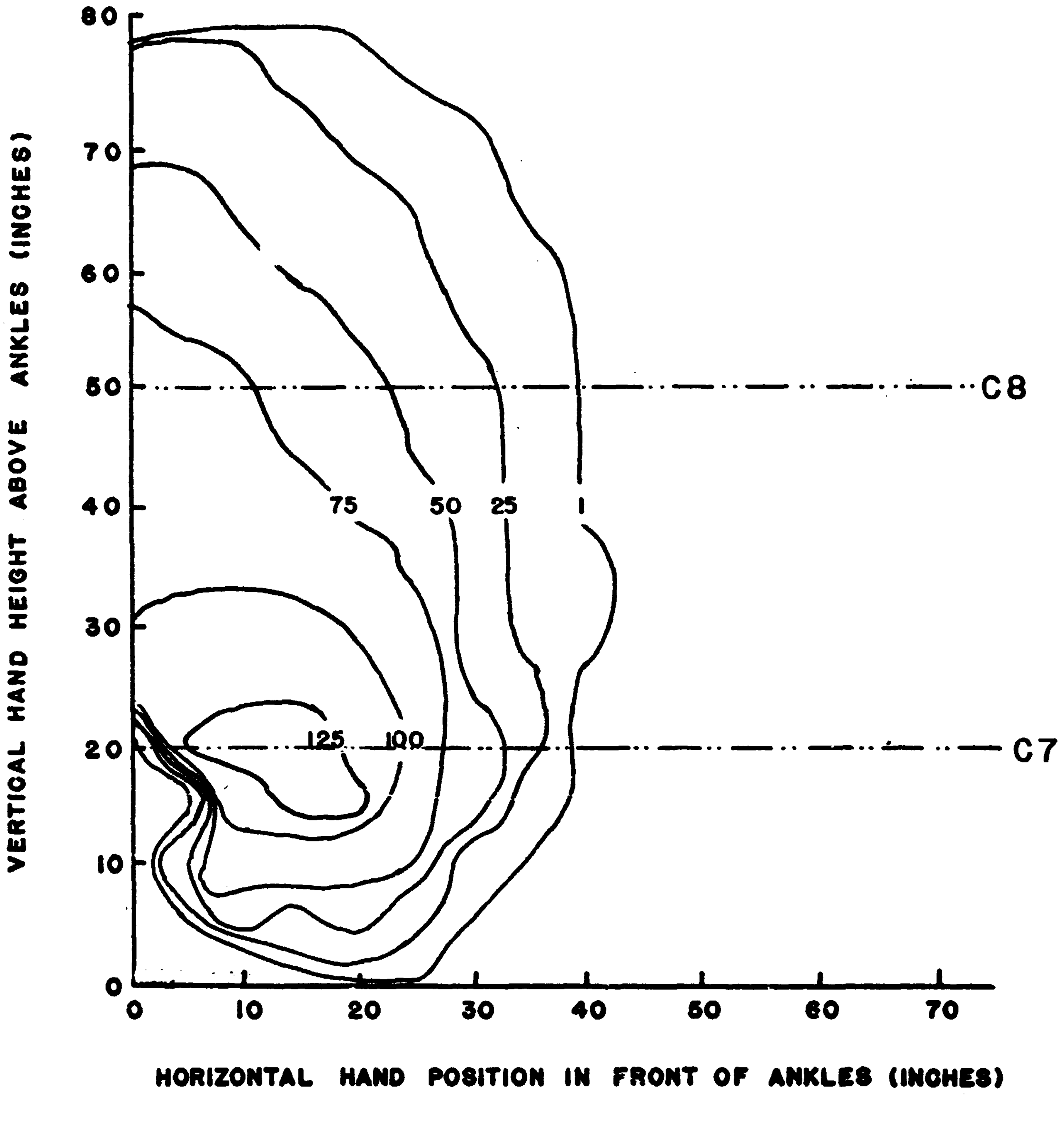
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 1.0 G

CLOTHING: SHIRTSLEEVED

TASK: PULLING



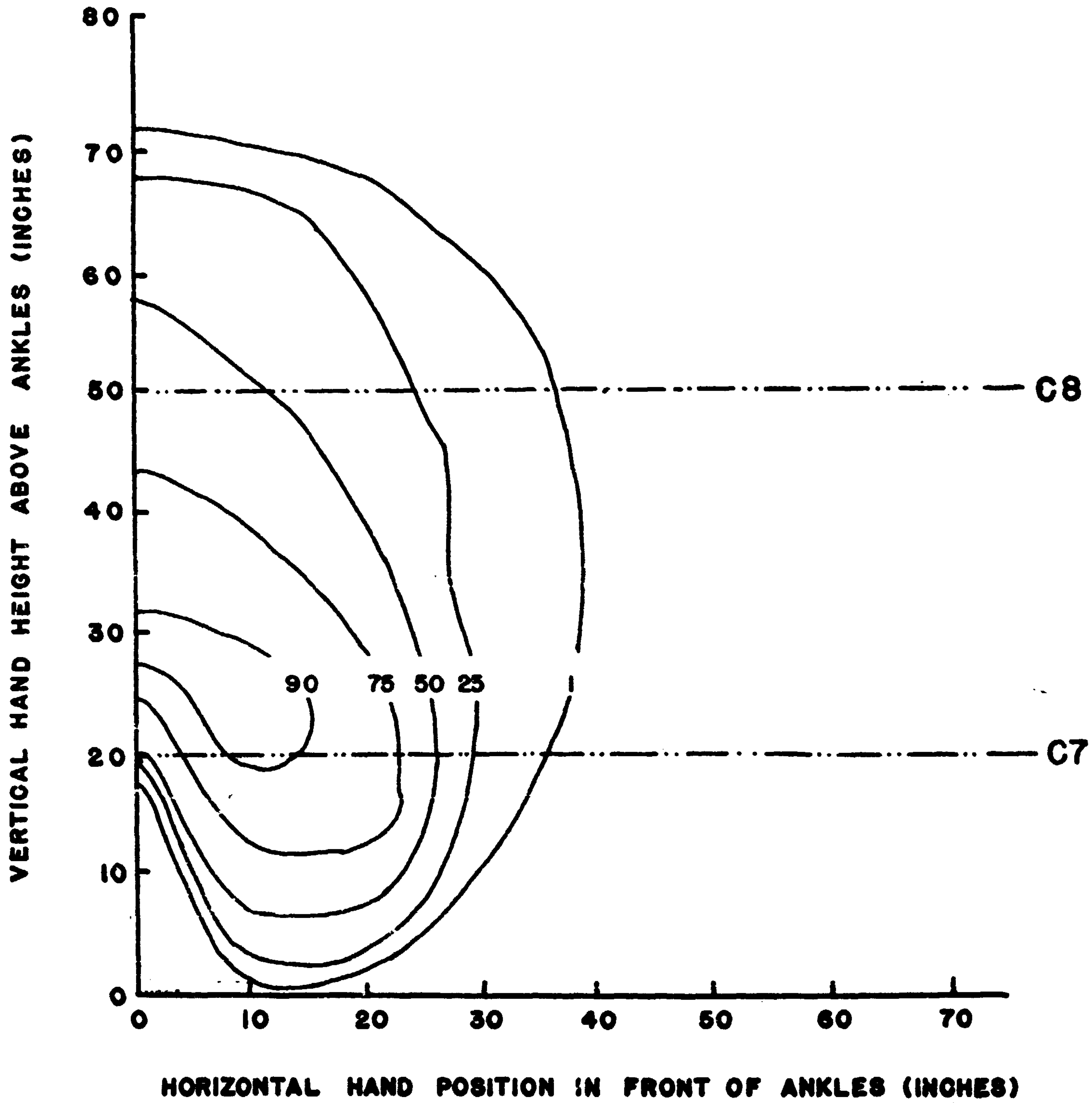
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 1.0 G

CLOTHING: SHIRTSLEEVED

TASK: PULLING



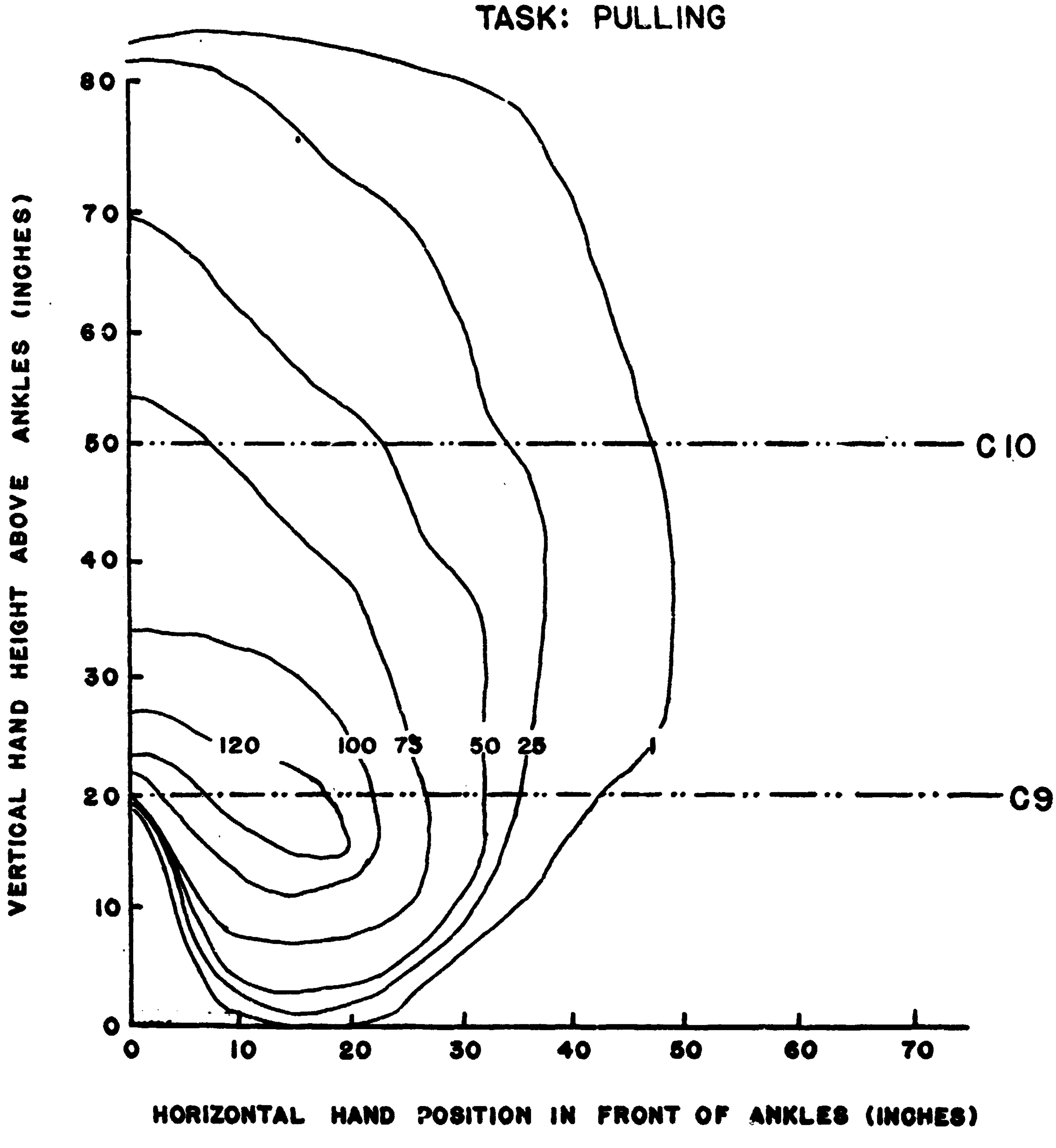
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 0.7 G

CLOTHING: SHIRTSLEEVED

TASK: PULLING



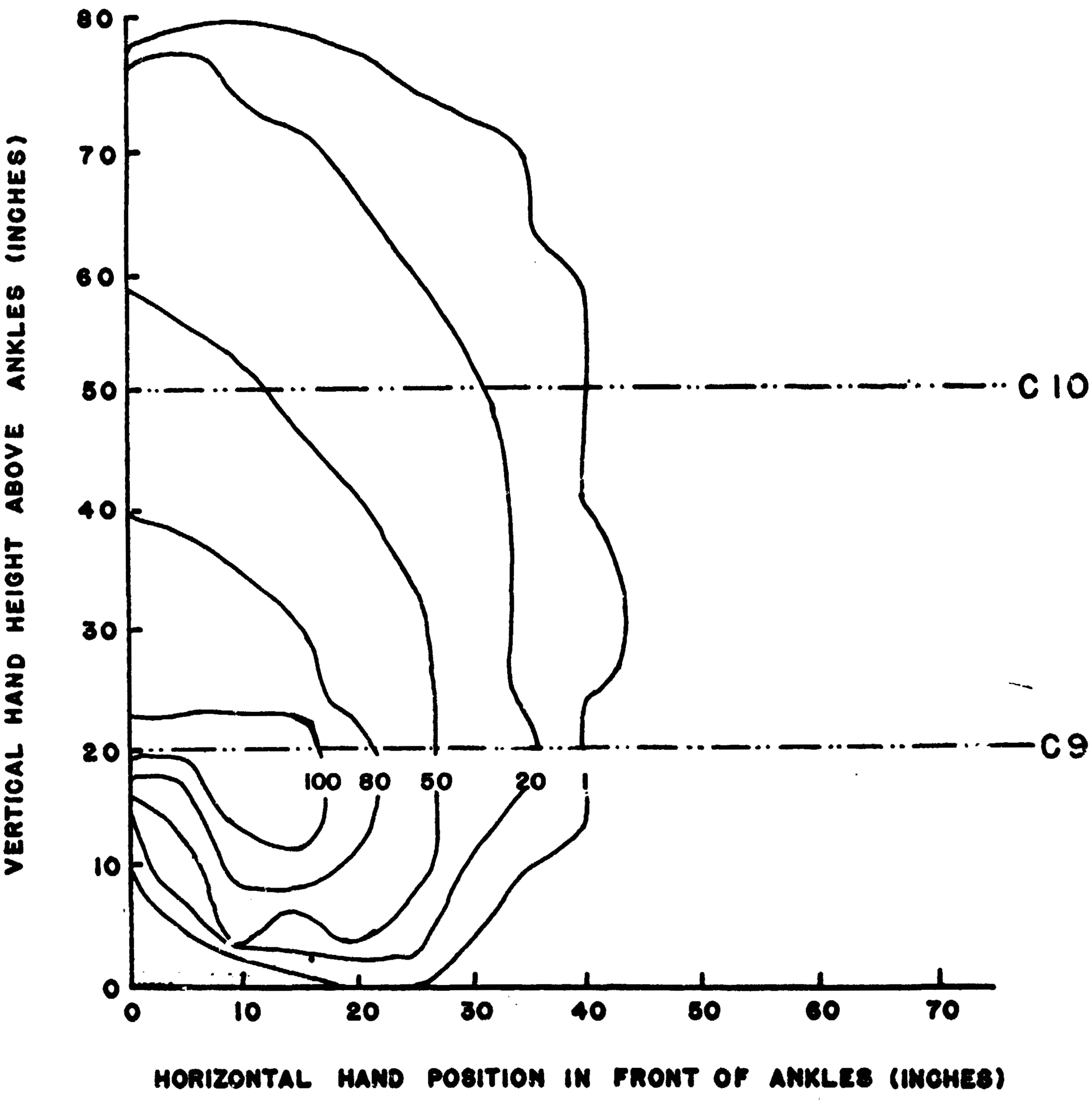
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50 %

GRAVITY: 0.7 G

CLOTHING: SHIRTSLEEVED

TASK: [redacted]PULLING



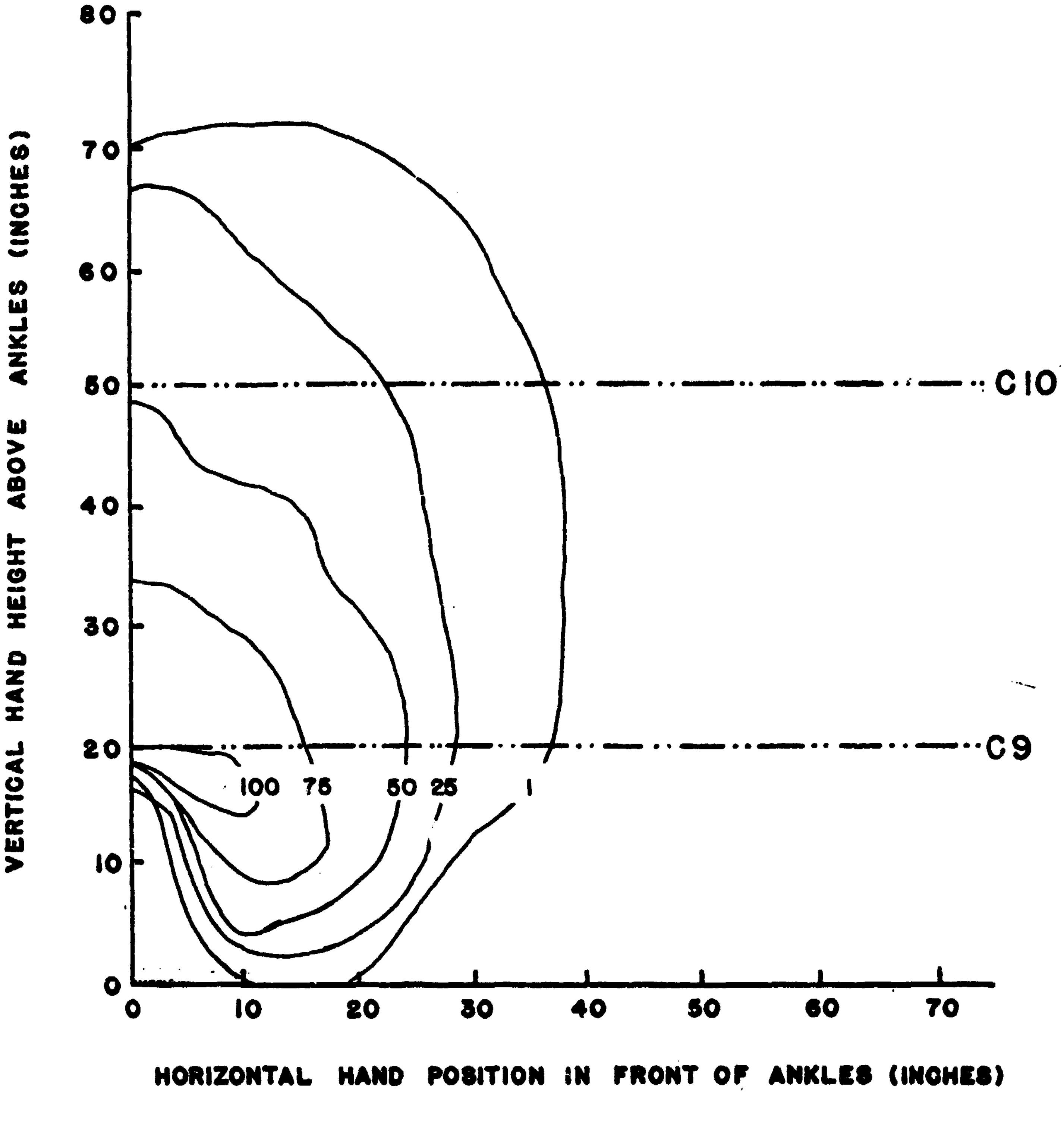
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

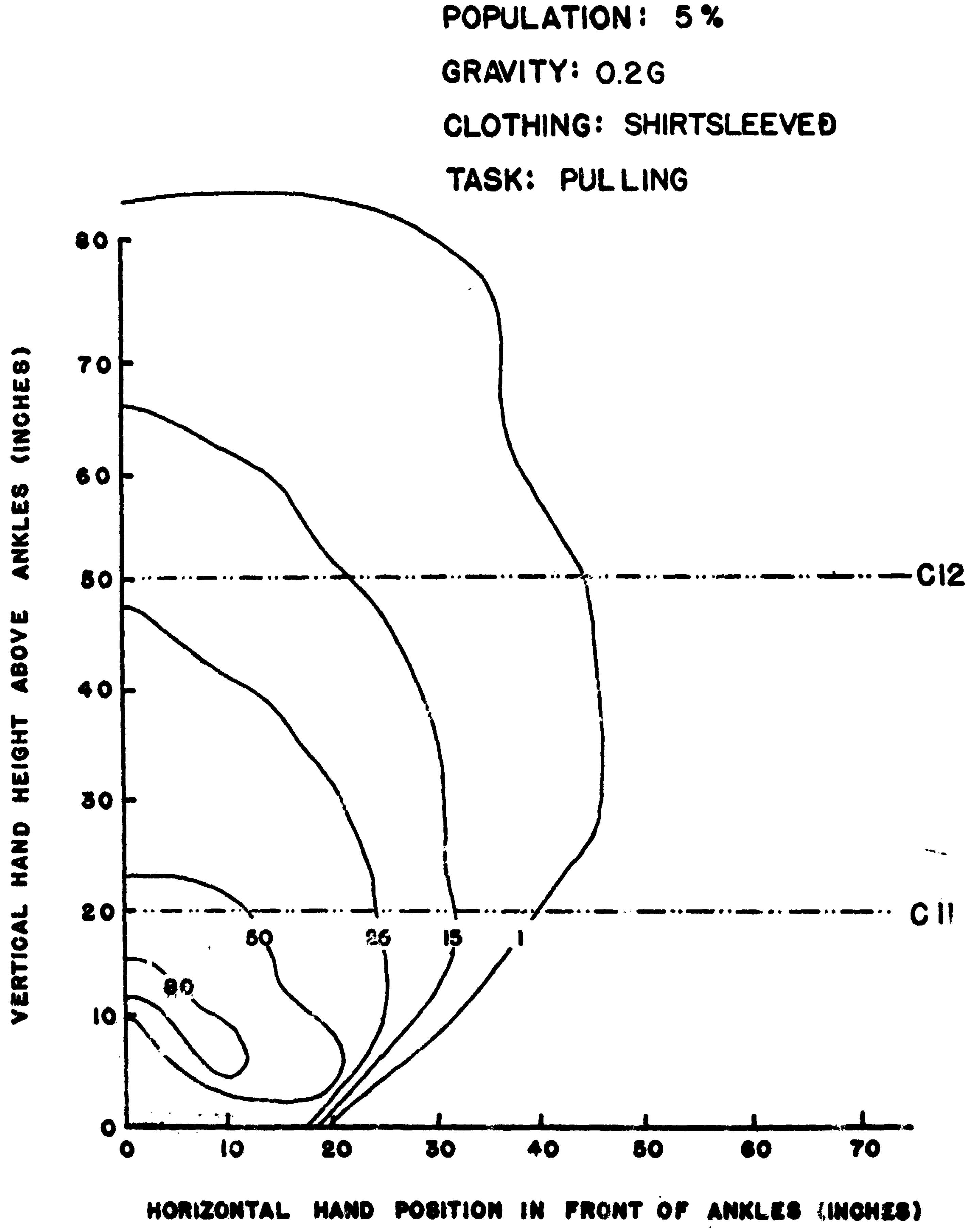
GRAVITY: 0.7 G

CLOTHING: SHIRTSLEEVED

TASK: PULLING



PREDICTED EQUAL HAND FORCE CAPABILITIES



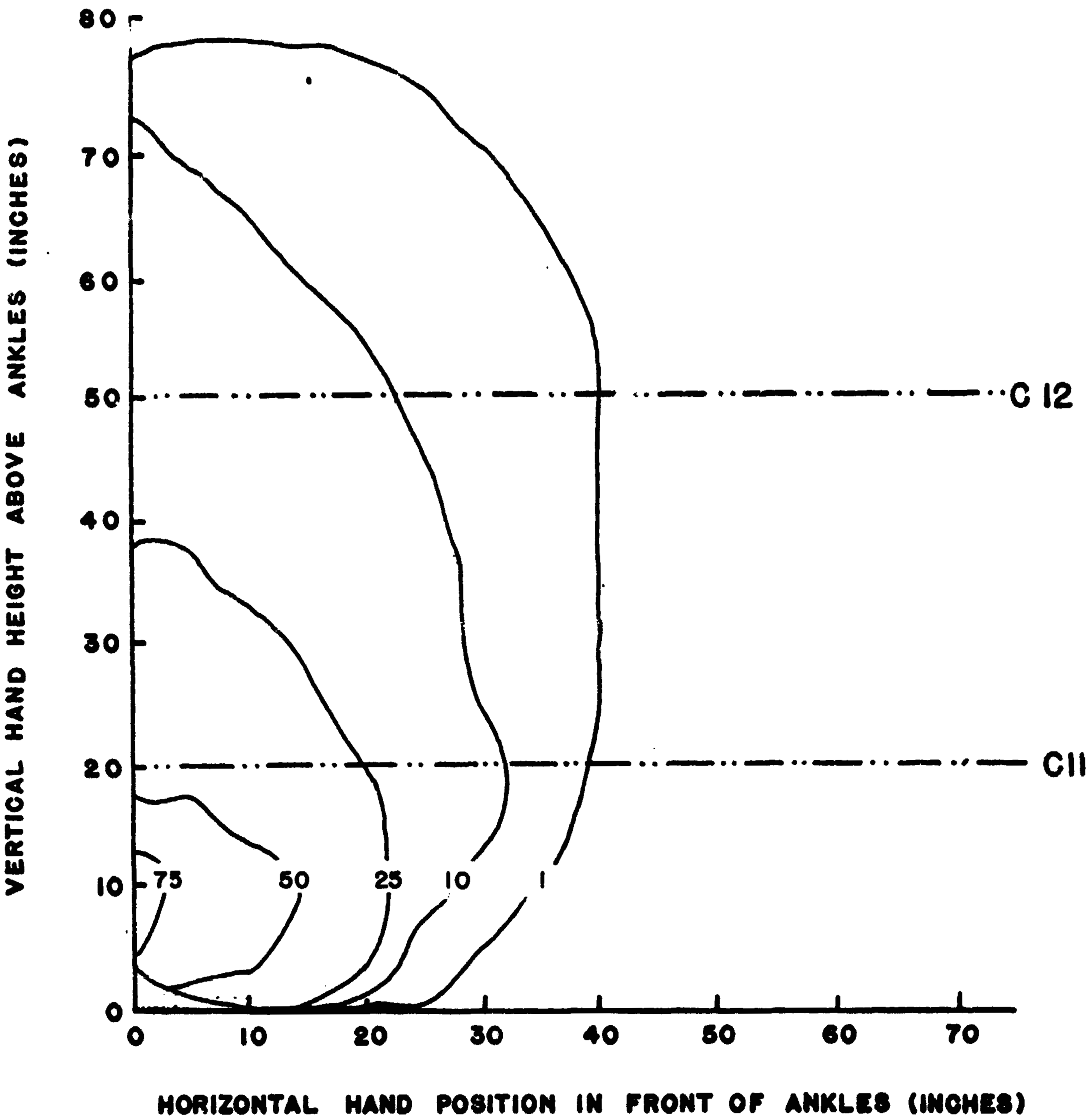
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 0.2 G

CLOTHING: SHIRTSLEEVED

TASK: PULLING



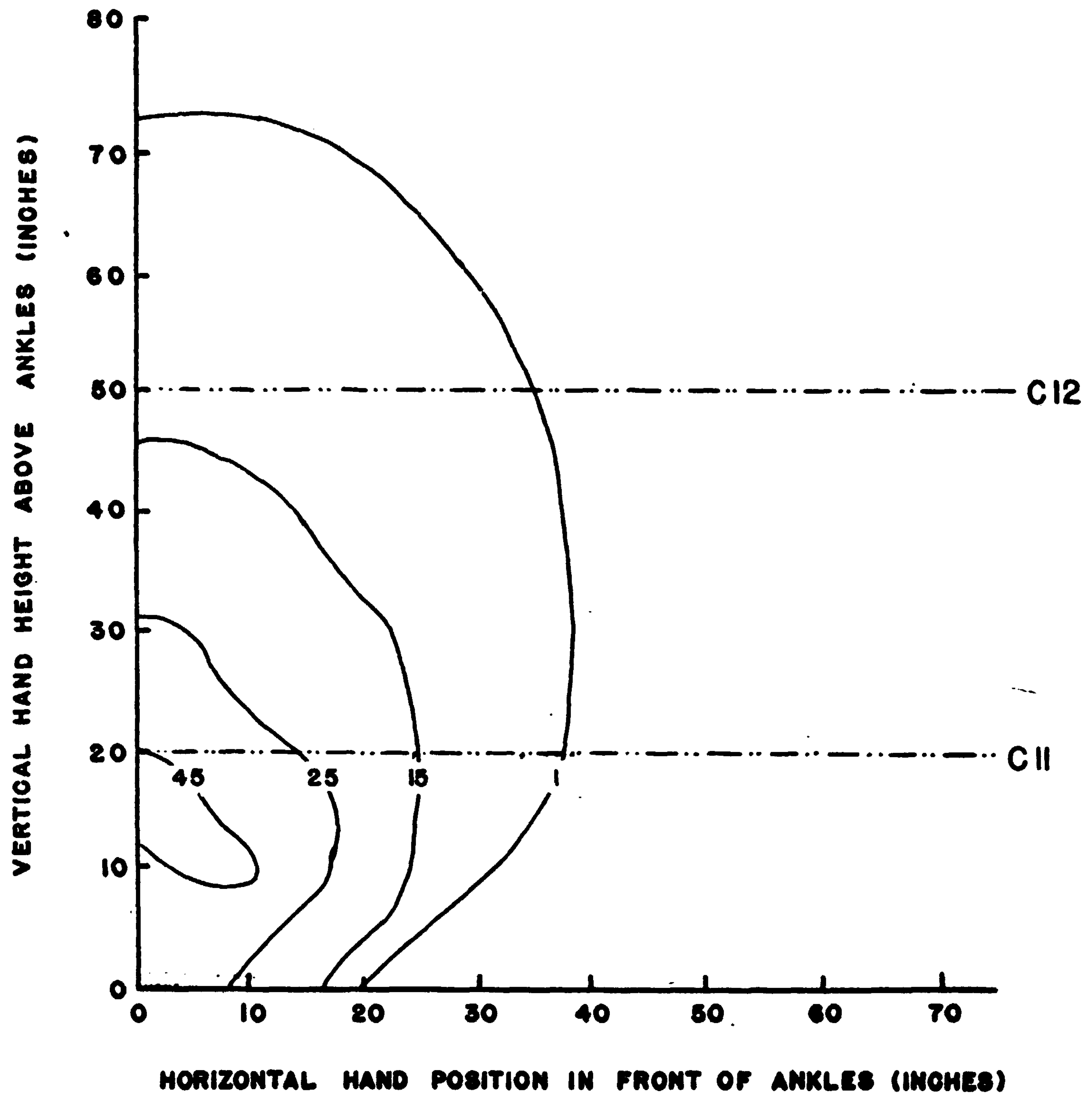
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 0.2 G

CLOTHING: SHIRTSLEEVED

TASK: PULLING



Shirt-Sleeved Two-Handed Force Predictions

during

Pushing

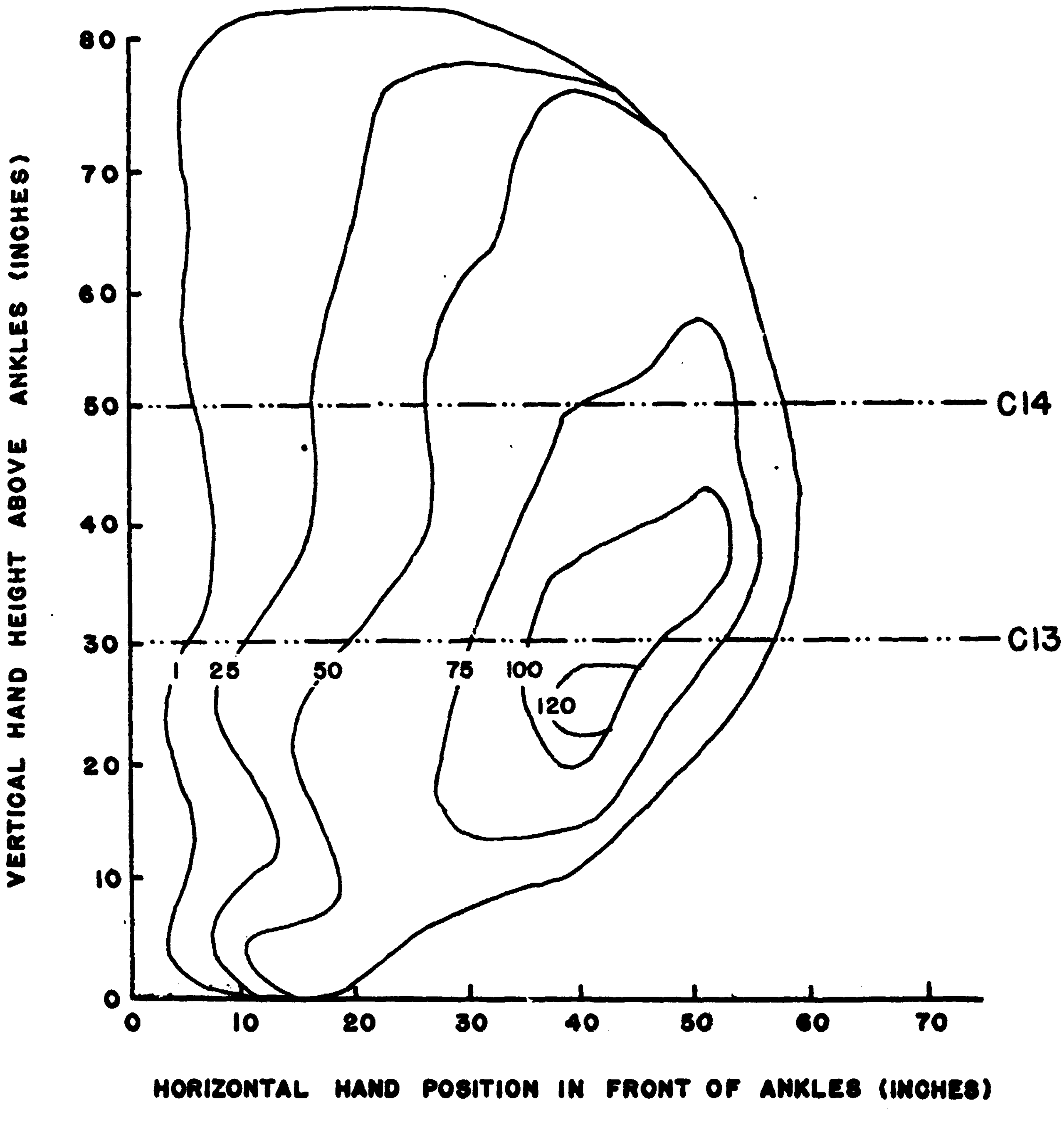
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 1.0 G

CLOTHING: SHIRTSLEEVED

TASK: PUSHING



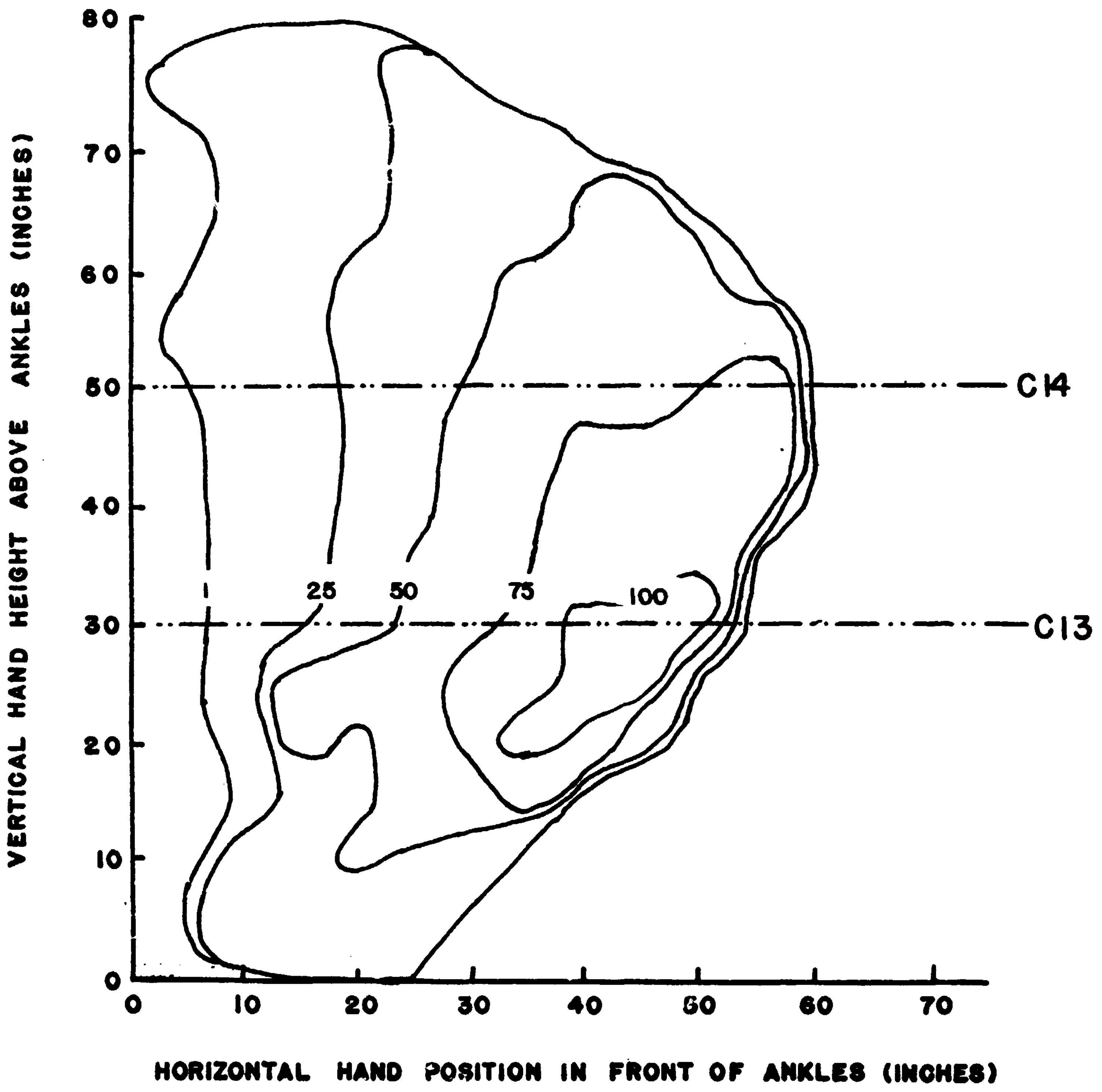
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 1.0 G

CLOTHING: SHIRTSLEEVED

TASK: PUSHING



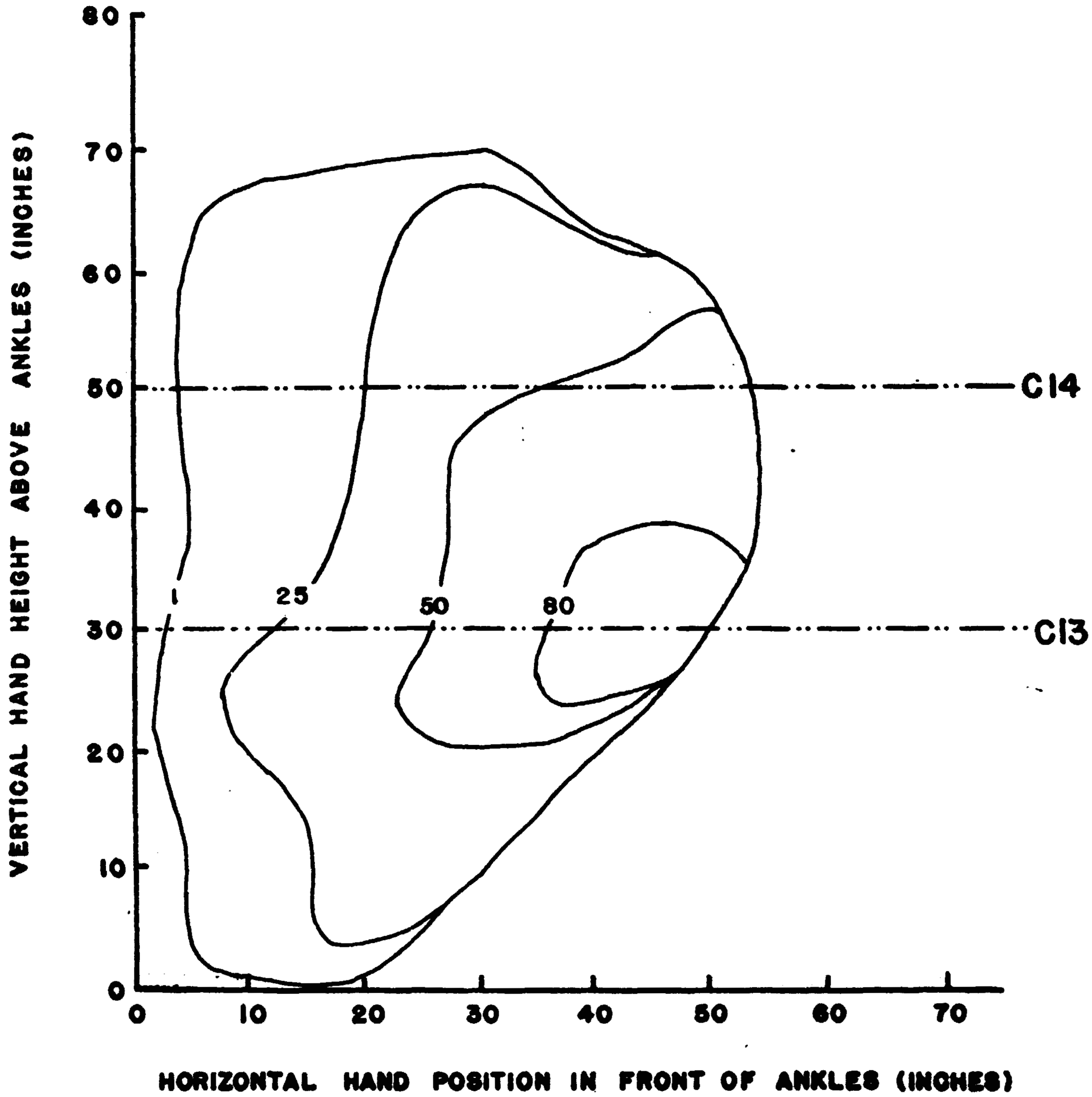
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 1.0 G

CLOTHING: SHIRTSLEEVED

TASK: PUSHING



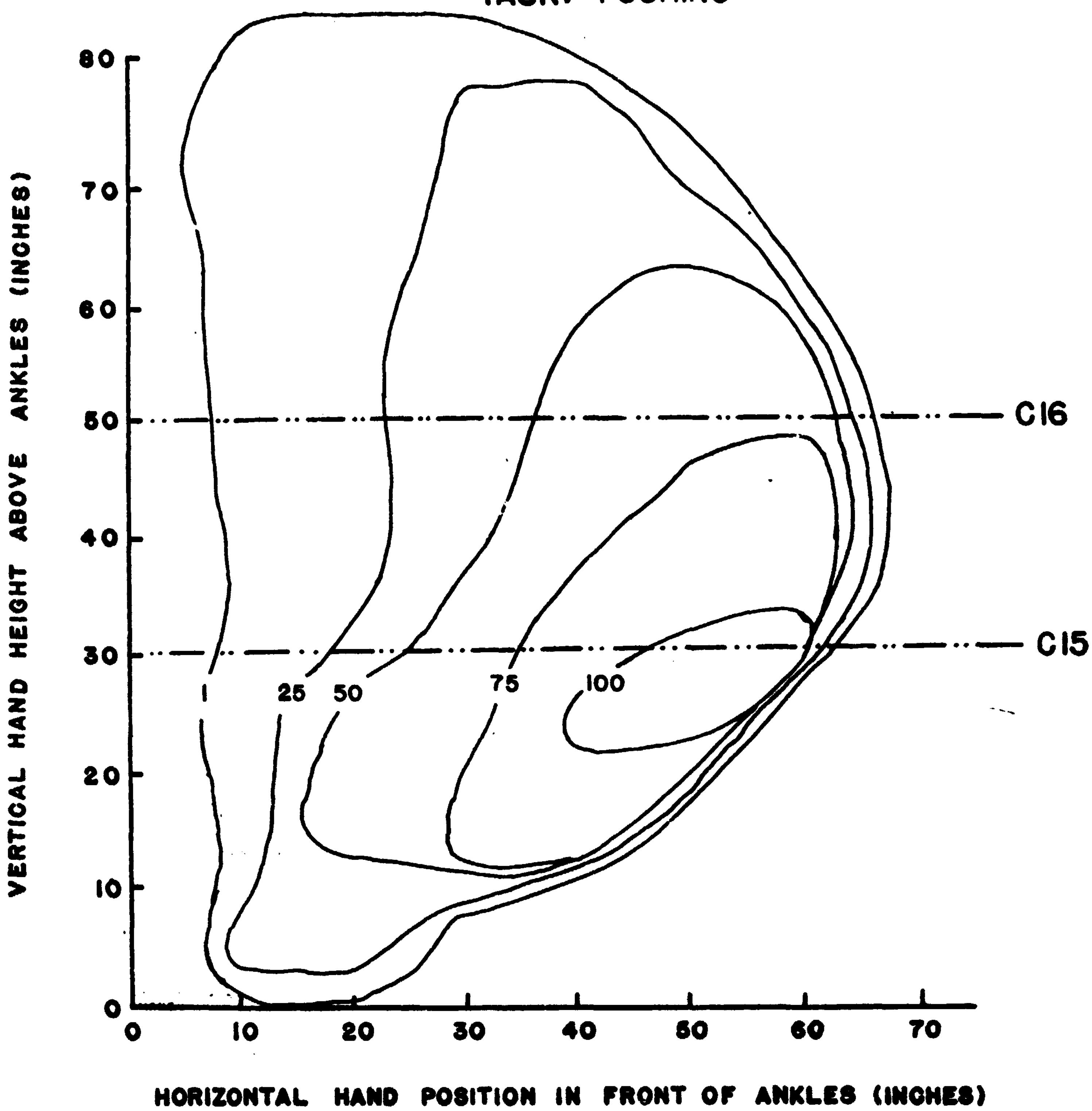
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 0.7G

CLOTHING: SHIRTSLEEVED

TASK: PUSHING



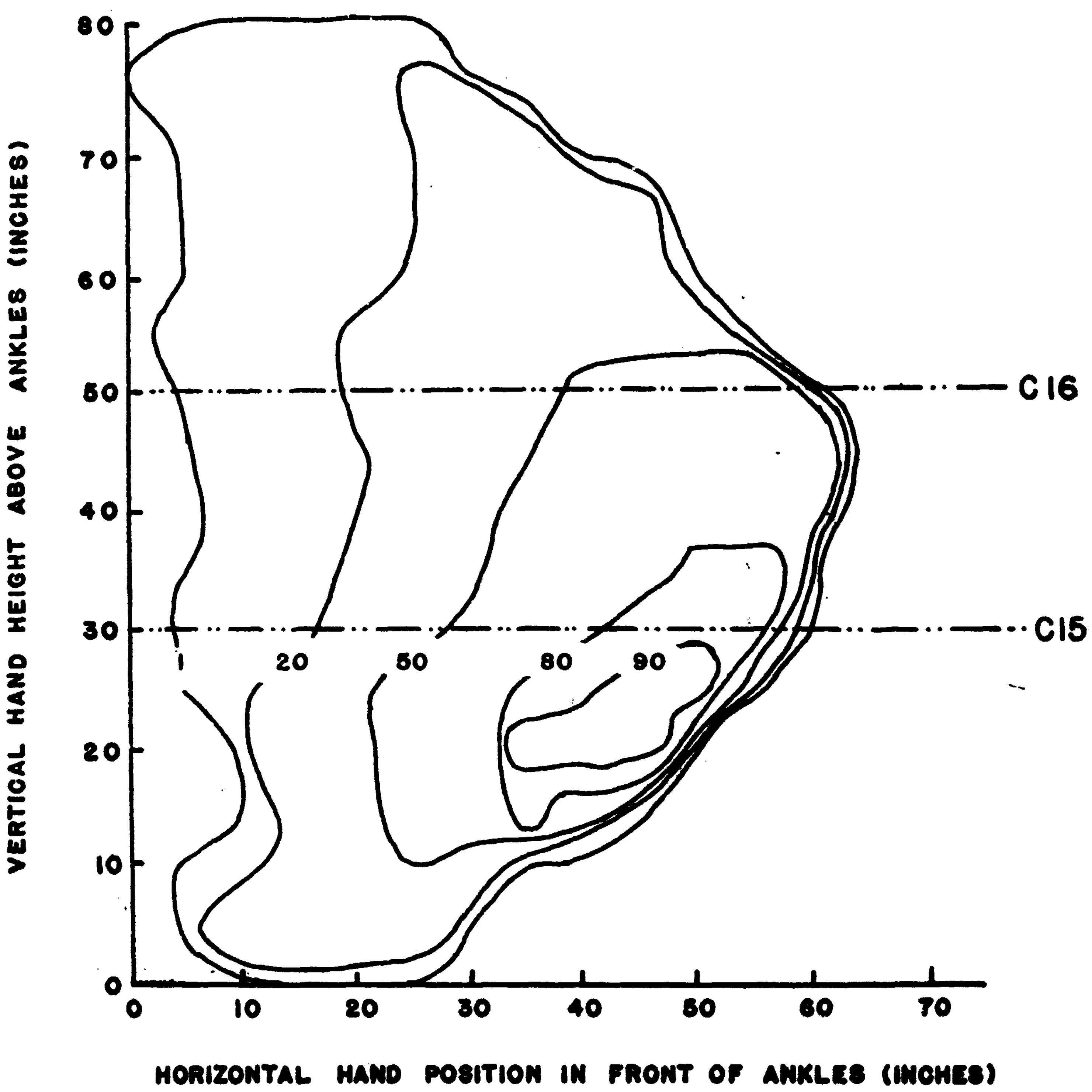
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 0.7G

CLOTHING: SHIRTSLEEVED

TASK: PUSHING



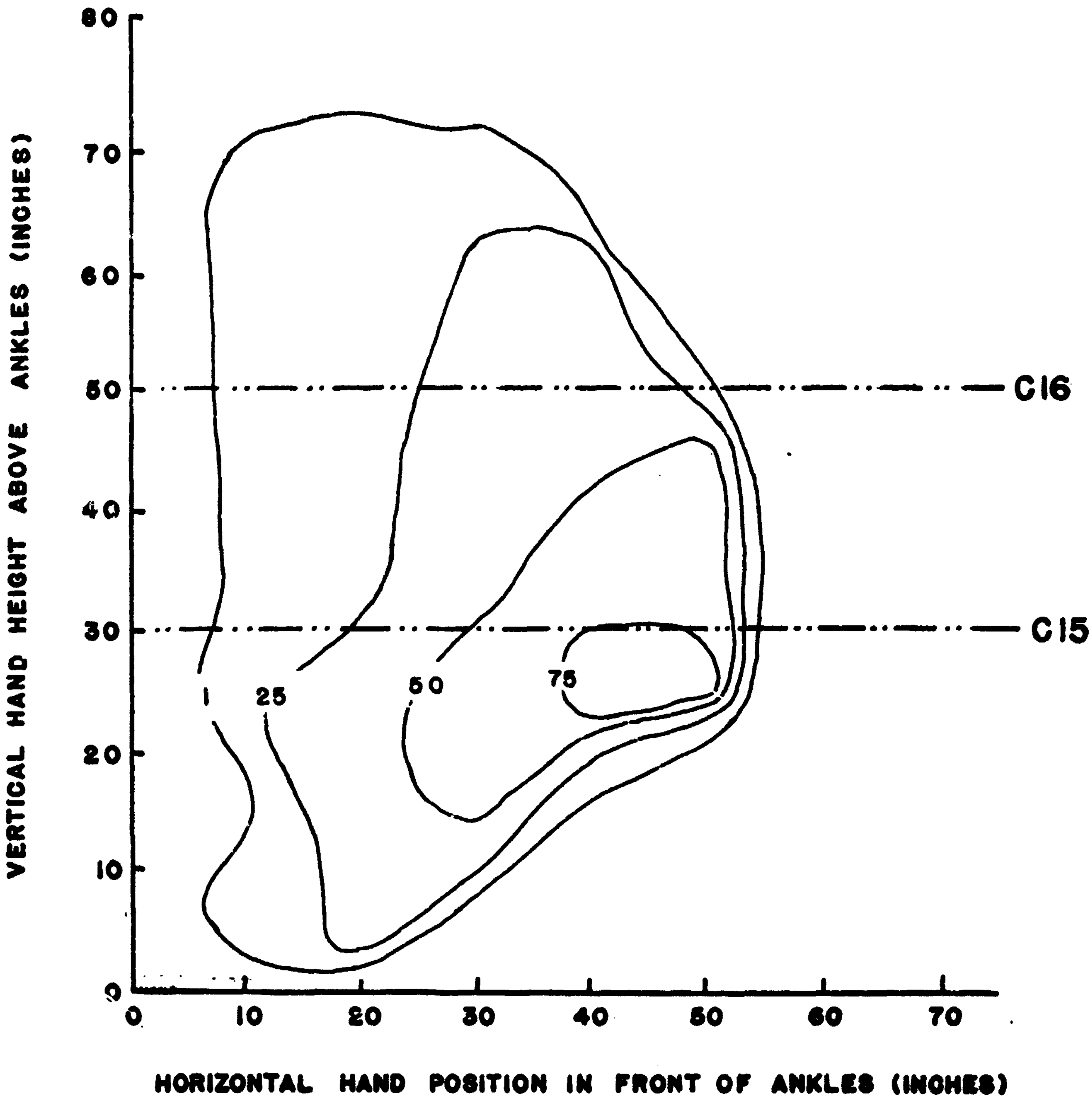
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 0.7 G

CLOTHING: SHIRTSLEEVED

TASK: PUSHING



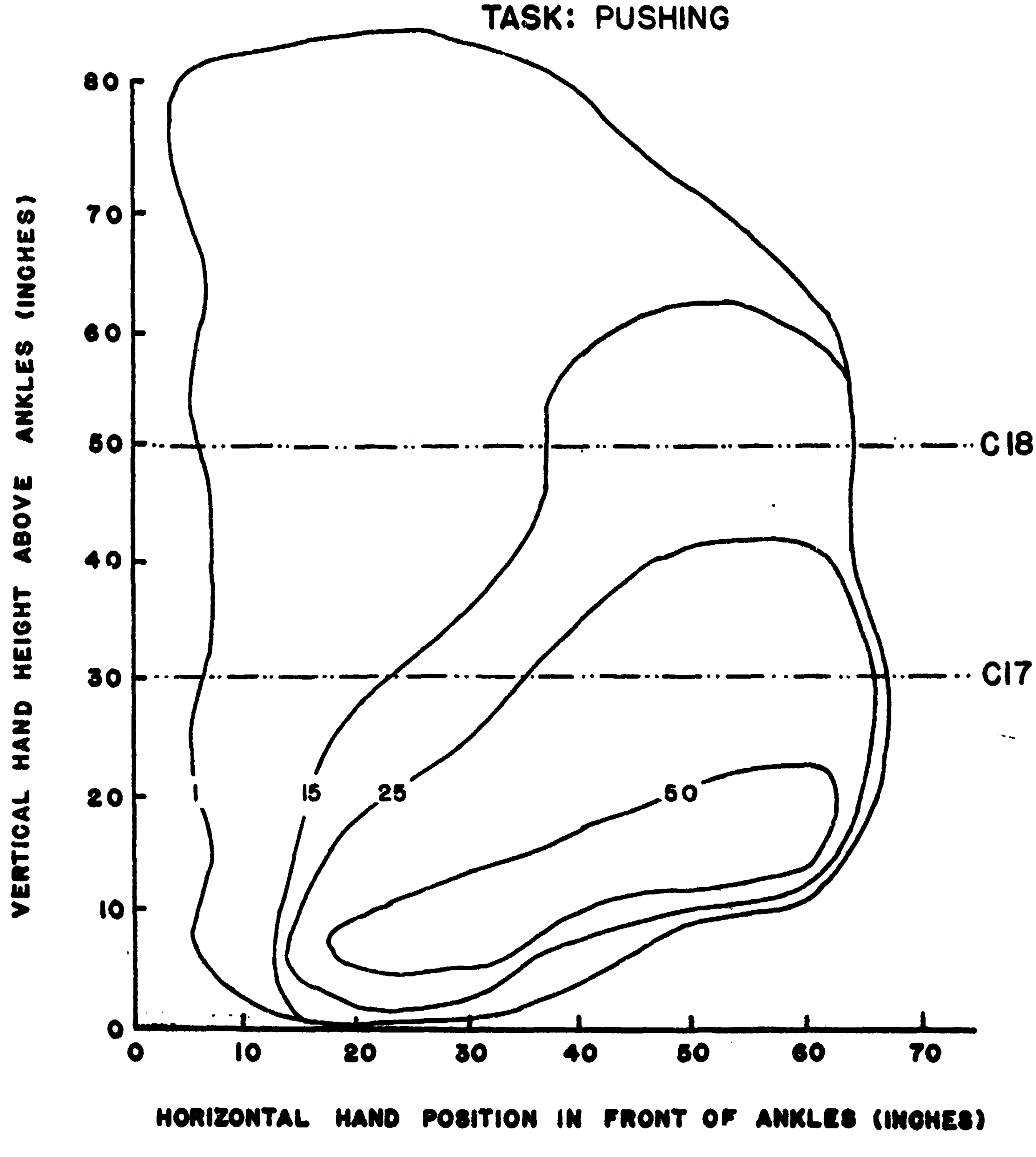
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 0.2 G

CLOTHING: SHIRTSLEEVED

TASK: PUSHING



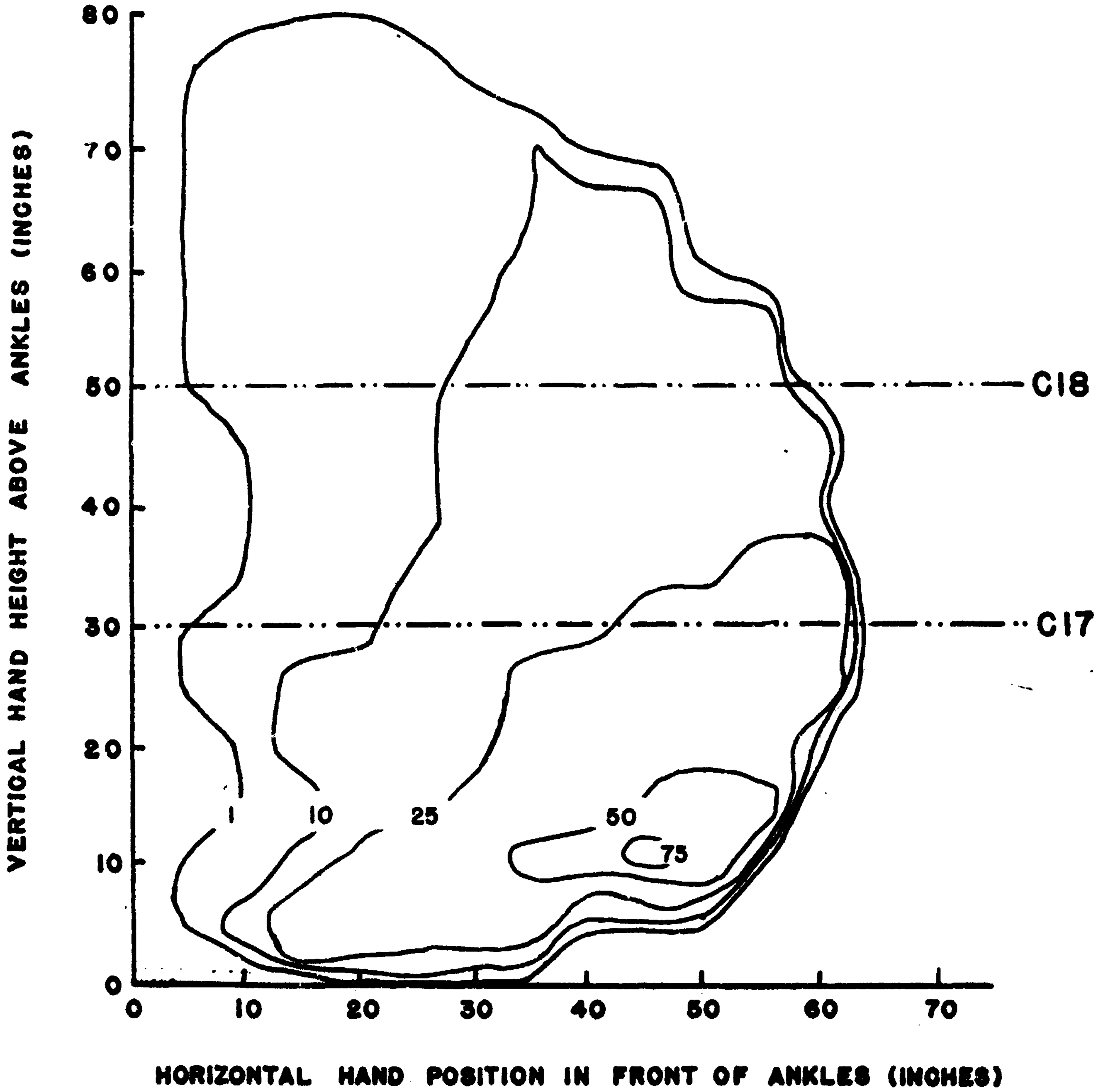
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 0.2G

CLOTHING: SHIRTSLEEVED

TASK: PUSHING



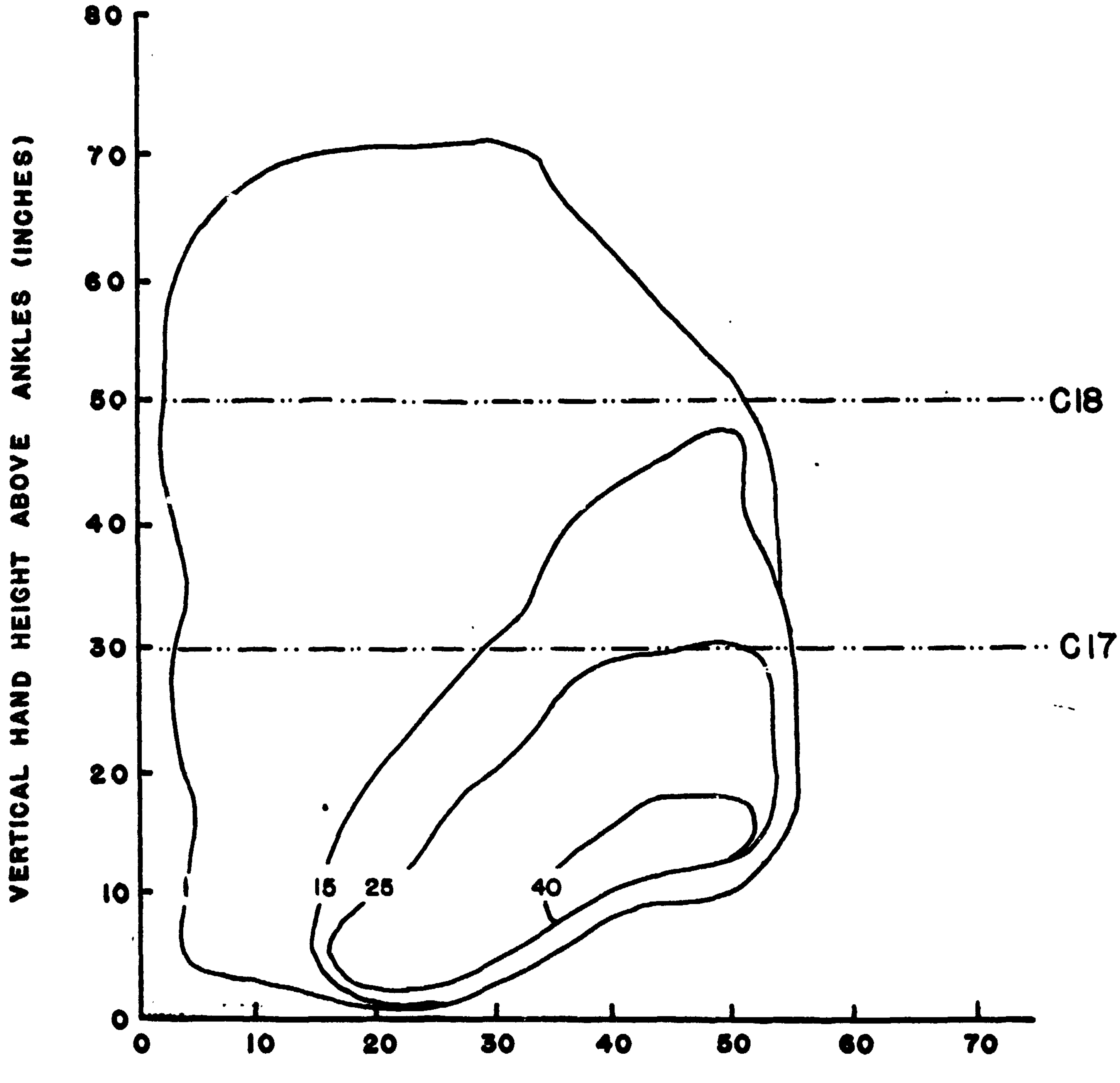
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 0.2 G

CLOTHING: SHIRTSLEEVED

TASK: PUSHING



Summary of Shirt-Sleeved Strength Predictions

The two-h. ded force predictions summarized in the preceding graphs display some general effects deemed worthy of specific note for design purposes.

Factors affecting shirt-sleeved lifting predictions.

1. When the hands are close to the knees, a person has the greatest lifting capability. Since the model restricted the hands from passing between the knees (i.e., only large objects were simulated), the predictions are believed to be lower (by as much as 40%) than for the situation where both hands could lift between the knees.

2. When lifting a load close to the body (i.e., the hands are within 10 inches in front of the ankles) where the load is at waist height, there is an approximate 30% decrease in capability from that resulting when the load is at the knee-high position. This is due to the mechanically poor advantage of the arms and back when the load is waist-high. Thus a well-trained weight lifter lifts heavy loads by accelerating them upwards (i.e., snatching from the floor) so that their momentum carries them through this "weak" area. Once the load is raised to the chest, a person can position his body under the load (provided that the handles on the object allow

his arms to reposition), and "push" the load upward using his legs and arms. This latter strength is about 20% lower than the strength capability when the hands are located close to the knees.

3. The area in front of and above a person wherein he can reach and produce at least a one-pound lifting force with both hands, remains approximately the same regardless of a reduced gravity of 0.2 g's. Also, in general, if the load is close to the body, a reduced gravity only slightly increases the lifting force capability.

4. If a person is attempting to lift an object that is not close to the body (i.e., about 30 inches horizontal to the ankles), a gravity of 0.2 g. reduces his lifting force capability to about one-half of that at 0.7 g. and 1.0 g. This is due to a lower body balance capability in the reduced 0.2 g. condition, which means that the person reaching out and lifting is impaired in using his buttocks and thighs to counterbalance the load in the hands. In other words, he topples forward more easily unless a restraint (e.g., a railing) is positioned to allow him to lean his thighs against it.

5. In general, the greater the horizontal distance (beyond 20 inches) that the hands are from the ankles

when lifting, the smaller the lifting capability (rule: estimate 4.0% reduction for each horizontal inch beyond 20 inches).

6. The population size and strength factor results in a prediction that 50% of the male population can produce 75% of the lifting force that 5% of the male population can produce, and 95% of the male population can produce half the lifting force that 5% of the male population can produce. In other words, if it is predicted that 5% of the male population can lift 100 pounds, then 50% can lift 75 pounds, and 95% can lift 50 pounds.

7. Also, it is predicted that the horizontal distance that a person can reach to and exert at least a one-pound lifting force must be reduced from that predicted for the larger 5% of the male population by eight inches if 95% of the male population is to be considered in the design.

Factors affecting shirt-sleeved pulling predictions.

1. The maximum pulling capability is achieved with the hands low (slightly below knee height) and slightly in front of the feet (18 inches from the ankles for 1.0 g. and 10 inches from the ankles for

0.2 g.). This low position allows the person to achieve a "backward leaning squat" wherein both his leg and back strength is well-used, in addition to his body weight assisting in pulling. A safety hazard does exist, since if the object being pulled-upon suddenly released, the person would have difficulty regaining his balance due to his pulling position. Thus he would either fall backwards, or be struck by the object, or both. Hence, low positions in pulling should be recommended with caution.

2. Moderately good pulling forces can be achieved with the hands at hip height if the hands are directly above the ankles. When hands are above the waist, each vertical inch added reduces the pull force by an average of 2.5%.

3. Reducing the gravity to 0.2 g. produces a pull force that is 50% less than that achieved with the better hand positions in a 1.0 g. environment. If the hands are slightly extended horizontally in front of the body, a reduced gravity has an even greater effect on pulling force capability.

4. Gravity does not appear to change the area wherein a person can reach an object and exert at least a one-pound pulling force on it.

5. The population size and strength factor does not have as great an effect on pulling capability as it does in lifting. For instance, 95% of the male population can achieve 70% of the pulling force produced by 5% of the male population. This is because pulling is usually a function of gravity and thus body size and weight are more critical than strength. Once again, this means that restraint systems by which a person can "steady" part of his body are critical, and can easily increase the pulling capability if they are carefully located.[1]

6. The area in which a person can reach and pull on an object with at least one pound of force is about seven inches smaller if 95% of the male population is included in the design instead of including only the larger 5% of the male population. The vertical area must be reduced by an average of ten inches if 95% rather than the larger 5% of the male population is included. These figures result from the variability in the size and strength of the male population.

[1]It is hoped that the analysis of restraint systems (e.g., hand holds, railings, etc.) on pushing and pulling capability can be included in future simulations.

Factors affecting shirt-sleeved pushing predictions.

1. Regardless of the gravity condition (1.0 g. - 0.2 g.) when the hands are located about 45 horizontal inches from the ankles, and between 15 to 25 inches above the ankles, the maximum pushing capability is predicted as being possible. When moving the hands either upward or in closer to the body, the pushing capability diminishes by about equal amounts. A poor pushing capability exists with the hands at shoulder height and over the ankles. Once again, it must be cautioned that the best position is a low one, and requires a person to stretch forward to gain the assistance of his body weight. If the object being pushed suddenly moves, the person could fall forward, if not ready to catch himself.

2. Reducing the gravity to 0.2 g.'s results in the highest pushing capability being diminished to 50% of its value in a 1.0 g. condition. The effect is even greater if the hands must be located close to over the ankles during the pushing activity.

3. Gravity does not appear to affect the area to which a person can reach and exert at least a one-pound push with both hands on an object.

4. The population variability has a relatively small effect on the maximum pushing capability. The pushing capability predicted for 5% of the male population is only reduced to 85% of its value if 95% of the male population is considered.

5. The population variability reduces the vertical height of the feasible, one-pound pushing area by 12 inches if 95% of the male population is designated, as opposed to designing for only the larger 5% of the male population.

Section IV

Results of Space Suited Strength Predictions

This section presents the two-handed force capability predictions for the male population when wearing an inflated A7L space suit with backpack (EMU mode). The constant force predictions are displayed in graphical form as a function of both the horizontal and vertical displacements of the hands in front of or above the ankles (as in the preceding Section III).

The order of reporting the force predictions is in three major subsections; the first for lifting, the second for pulling, and the last for pushing. Within each subsection, the graphs are divided into the three gravity conditions (1.0, 0.7, and 0.2 g.'s). For each gravity condition a sequence of three graphs present the force predictions for 5%, 50%, and 95% of the male population (as defined by Table IV at the end of Section III).

In addition to the graphs presented in this section, Appendix C displays a set of force predictions for specific vertical hand heights. The hand heights chosen for this presentation are depicted by horizontal section lines drawn across the equal hand force graphs. The numbers at the end of these lines refer to the specific graphs found in Appendix C. The corresponding graphs in Appendix C are marked in the upper right hand corner with the same numbers. The graphs in Appendix C also display the work envelope dimensions and the gross body positions (with reference to a set of standard positions) required by a person exerting his maximal hand force.[1]

A summary section describes the major factors that affect the hand force of an individual wearing a space suit. Implications regarding safety are also discussed.

[1]Specific body positions and the part of the body limiting the hand forces are outputted from the program and can be obtained for specific tasks upon request to the Engineering Human Performance Laboratory, Department of Industrial Engineering, The University of Michigan, Ann Arbor, Michigan, 48105.

Space Suited Two-Handed Force Predictions

during

Lifting

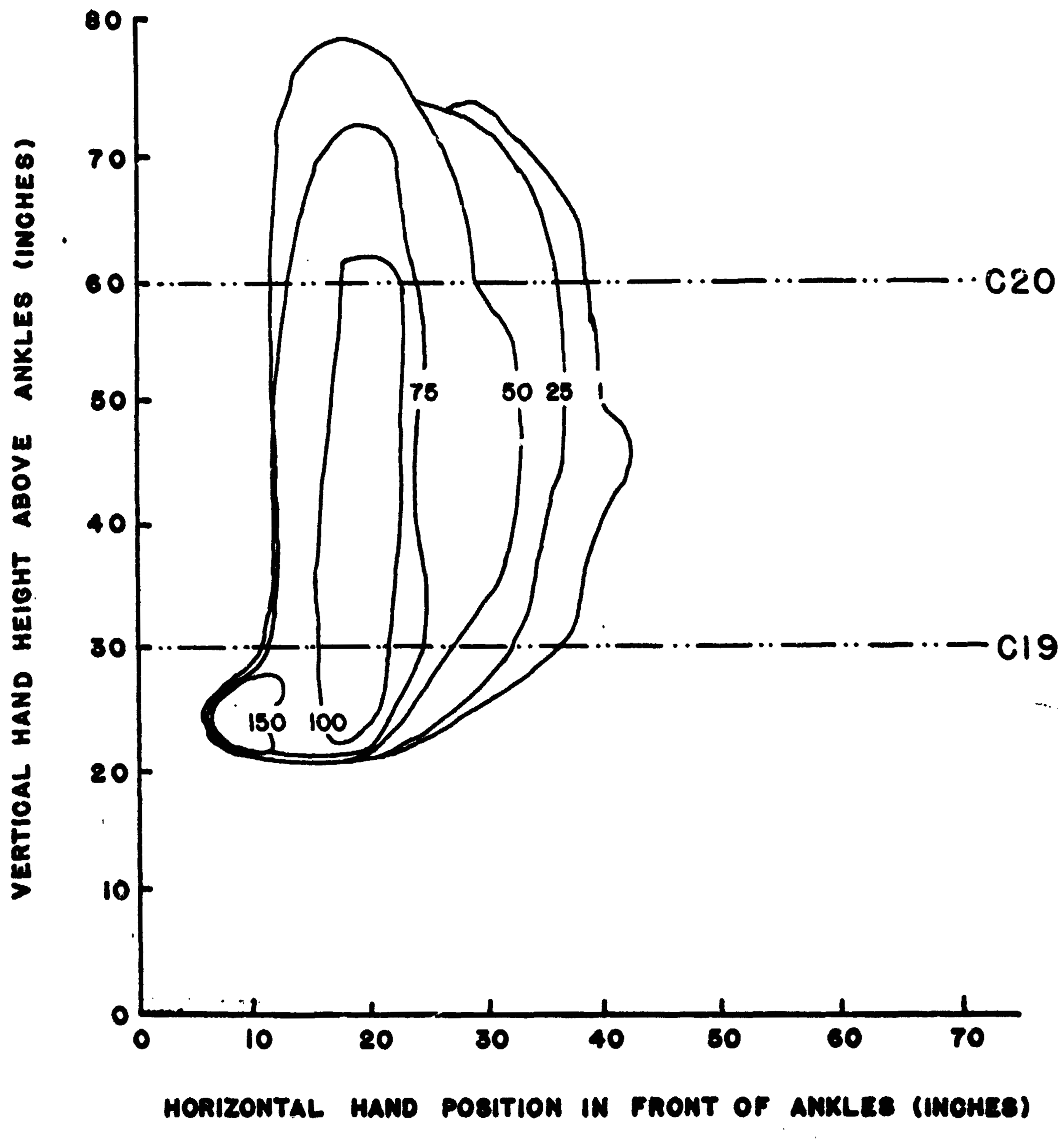
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 1.0 G

CLOTHING: SUITED

TASK: LIFTING



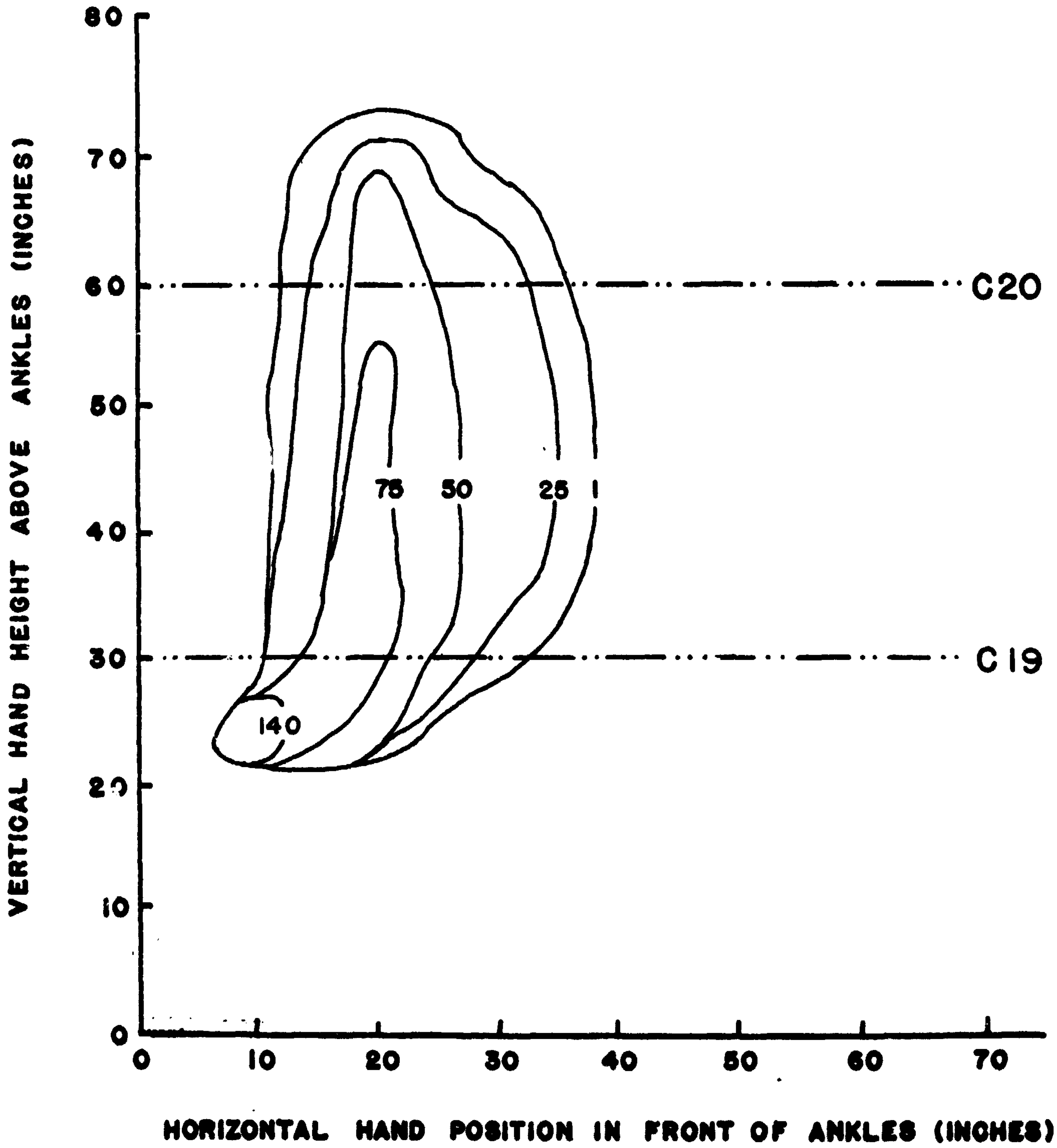
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50 %

GRAVITY: 1.0 G

CLOTHING: SUITED

TASK: LIFTING



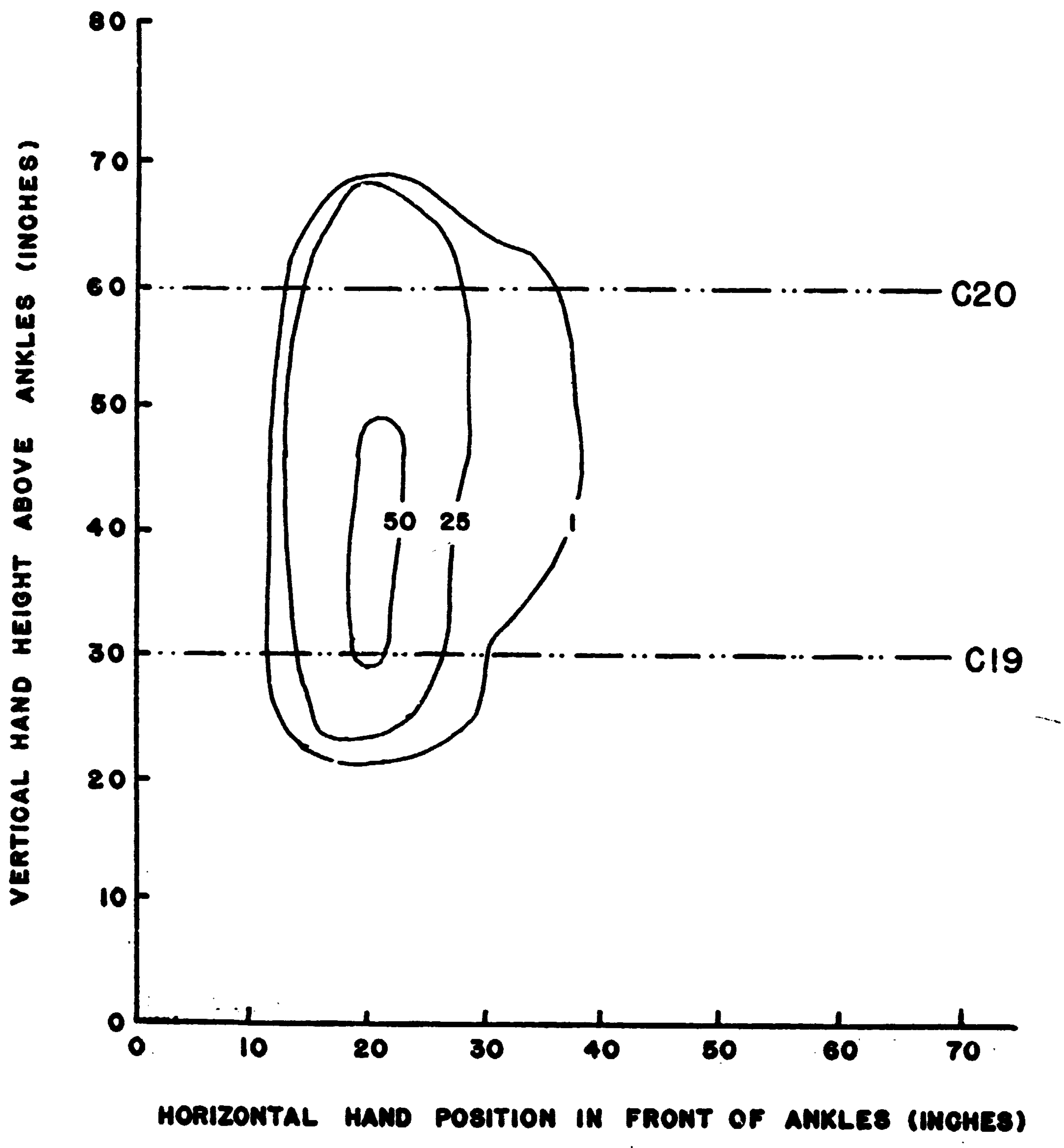
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 1.0G

CLOTHING: SUITED

TASK: LIFTING



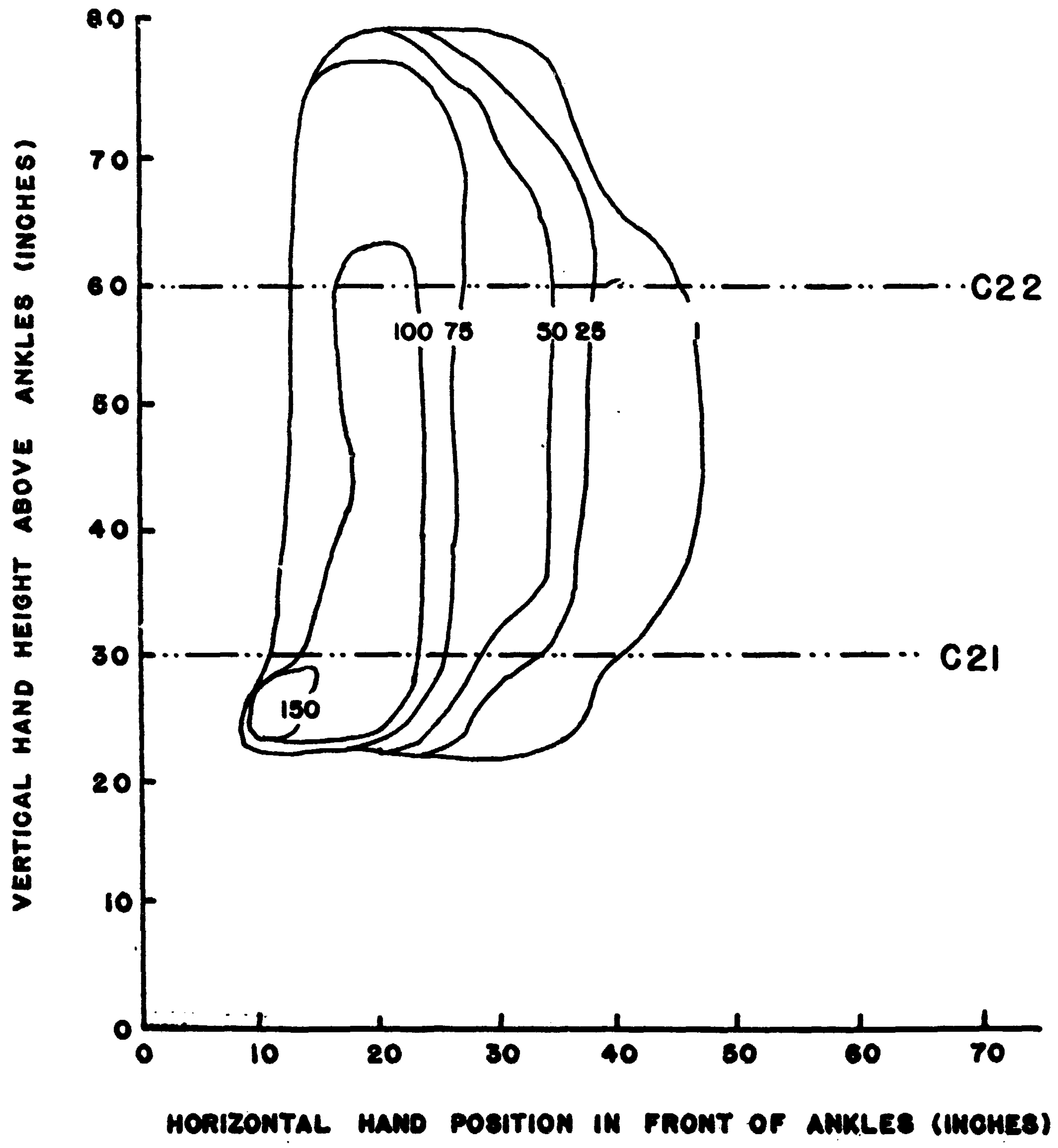
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 0.7 G

CLOTHING: SUITED

TASK: LIFTING



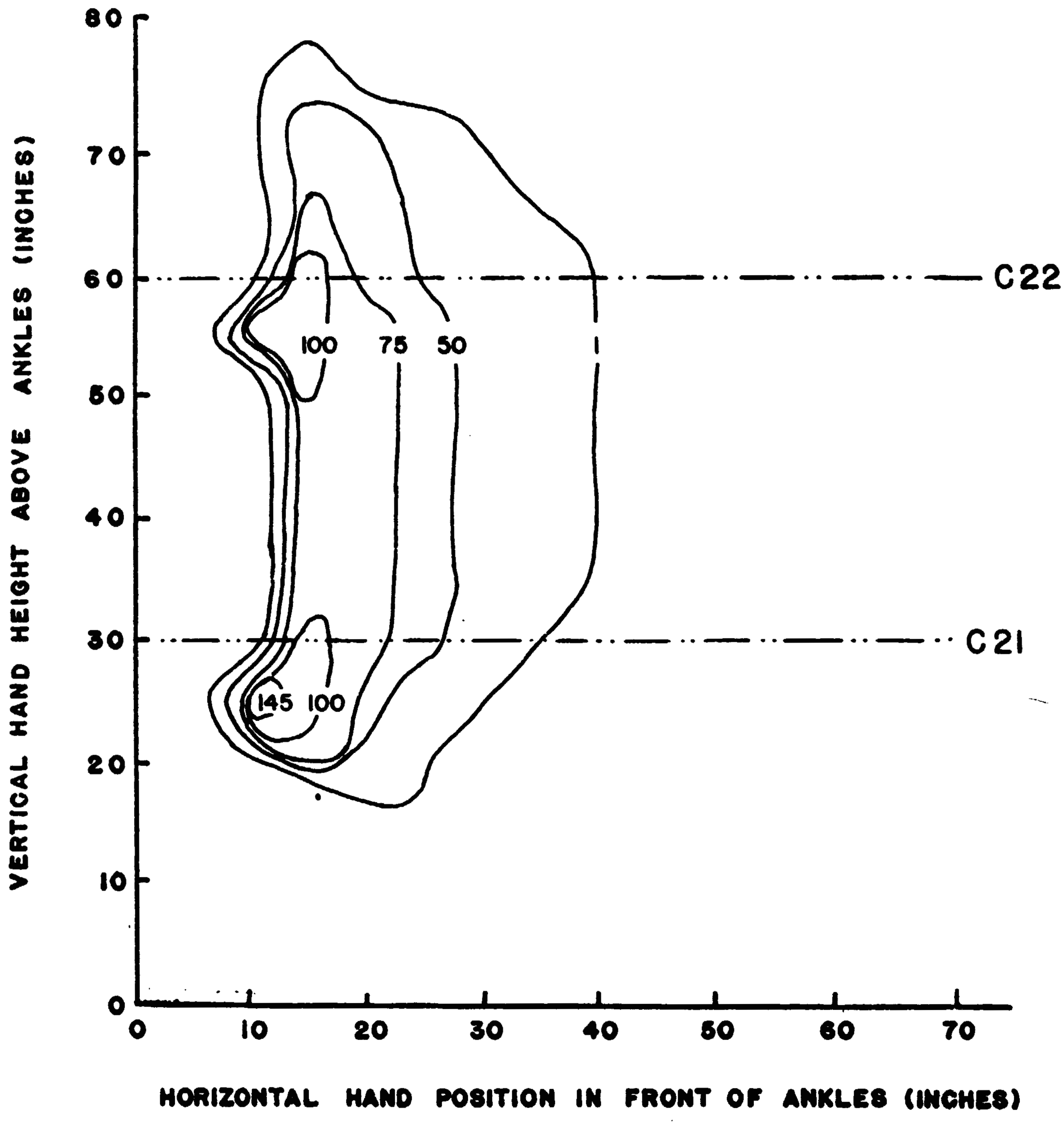
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 0.7 G

CLOTHING: SUITED

TASK: LIFTING



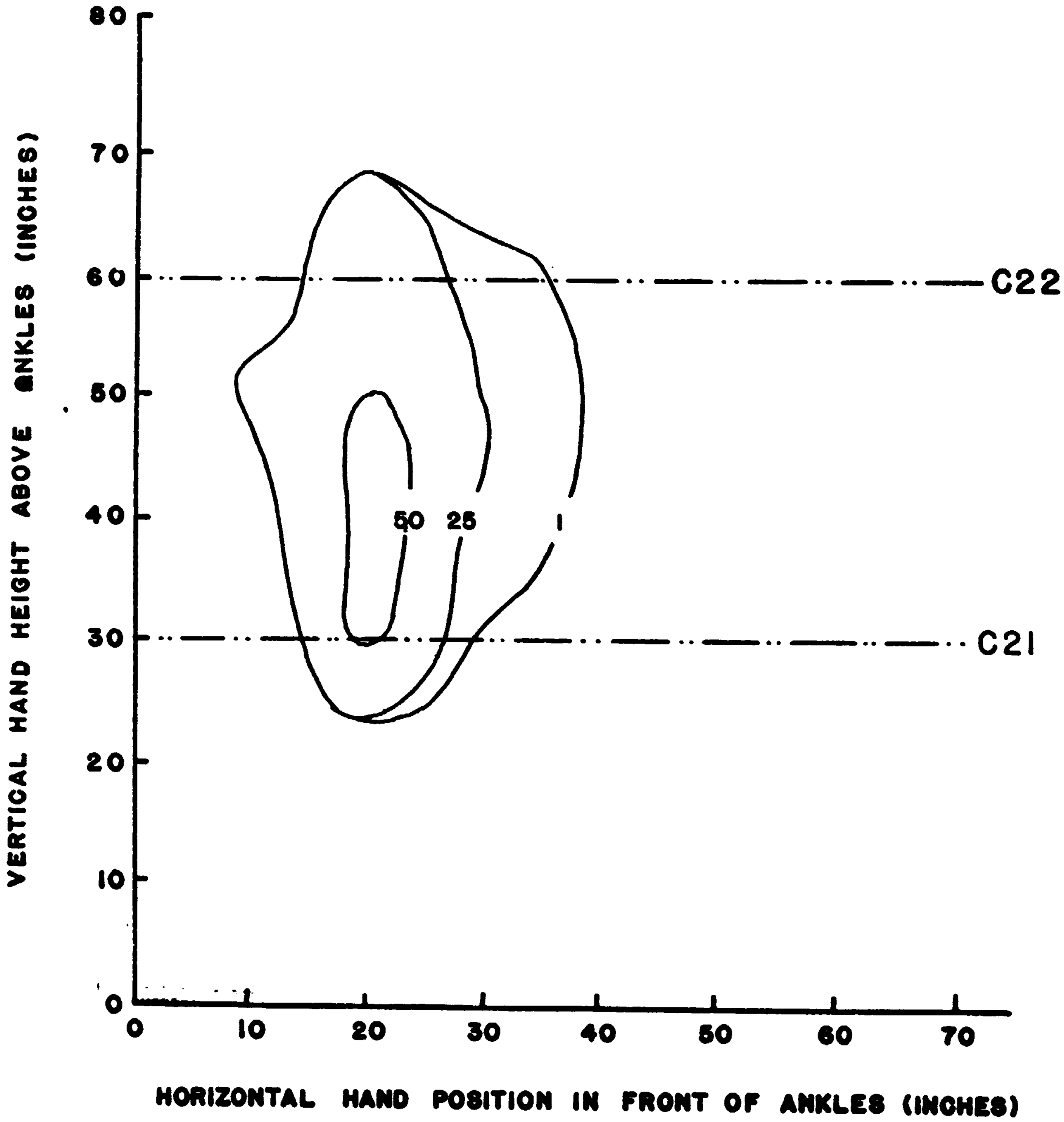
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 0.7 G

CLOTHING: SUITED

TASK: LIFTING



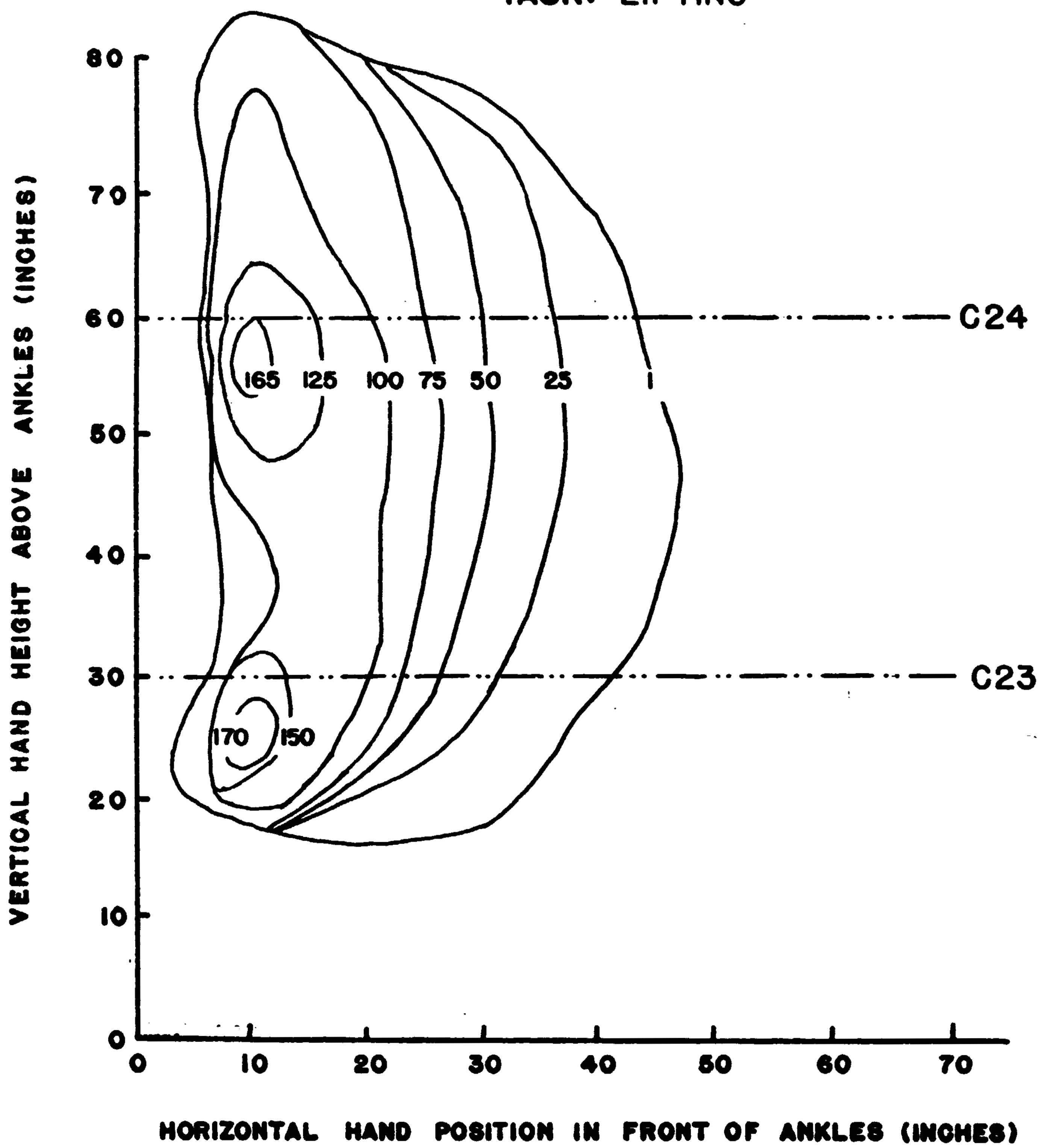
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 0.2 G

CLOTHING: SUITED

TASK: LIFTING



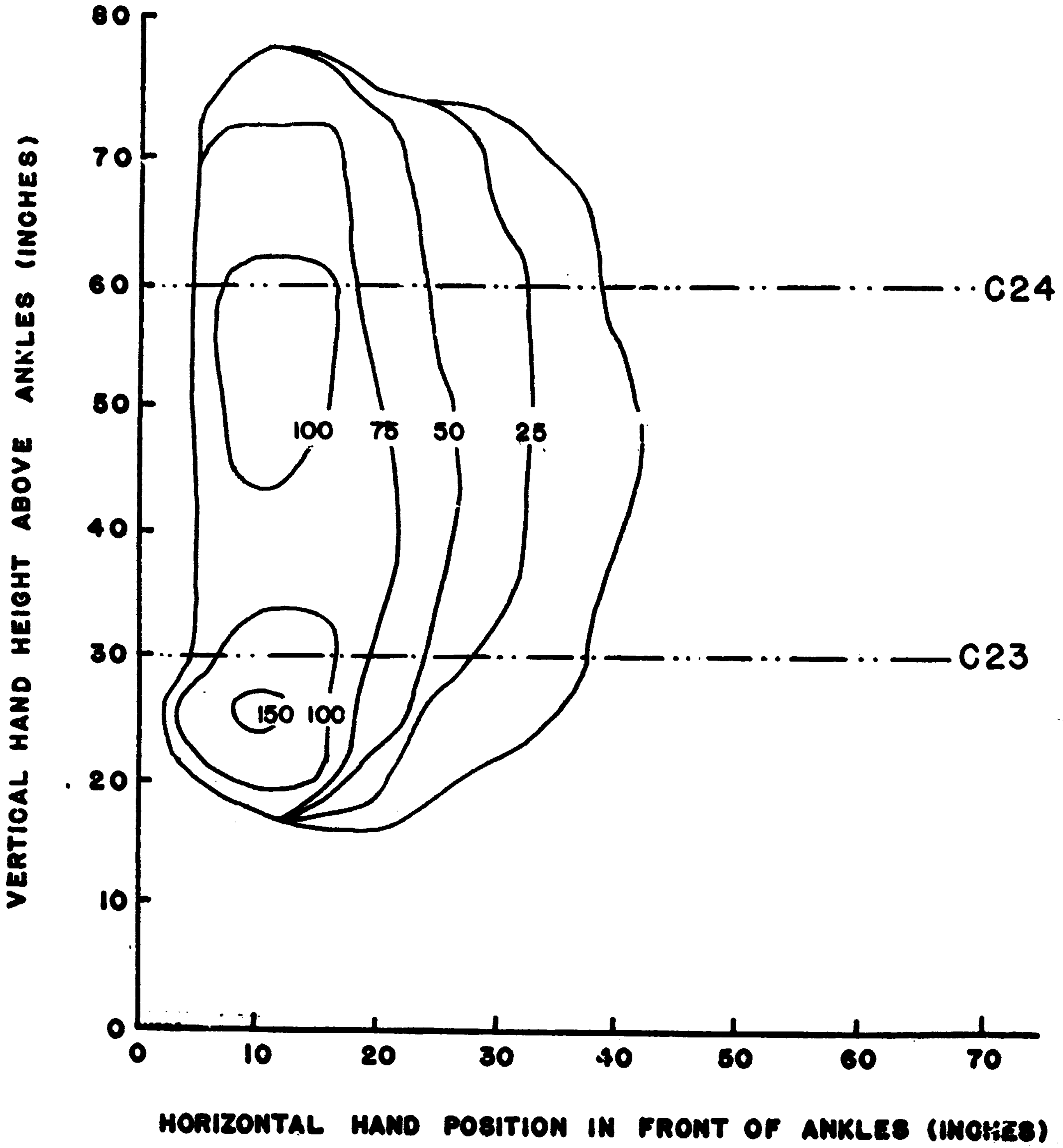
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 0.2G

CLOTHING: SUITED

TASK: LIFTING



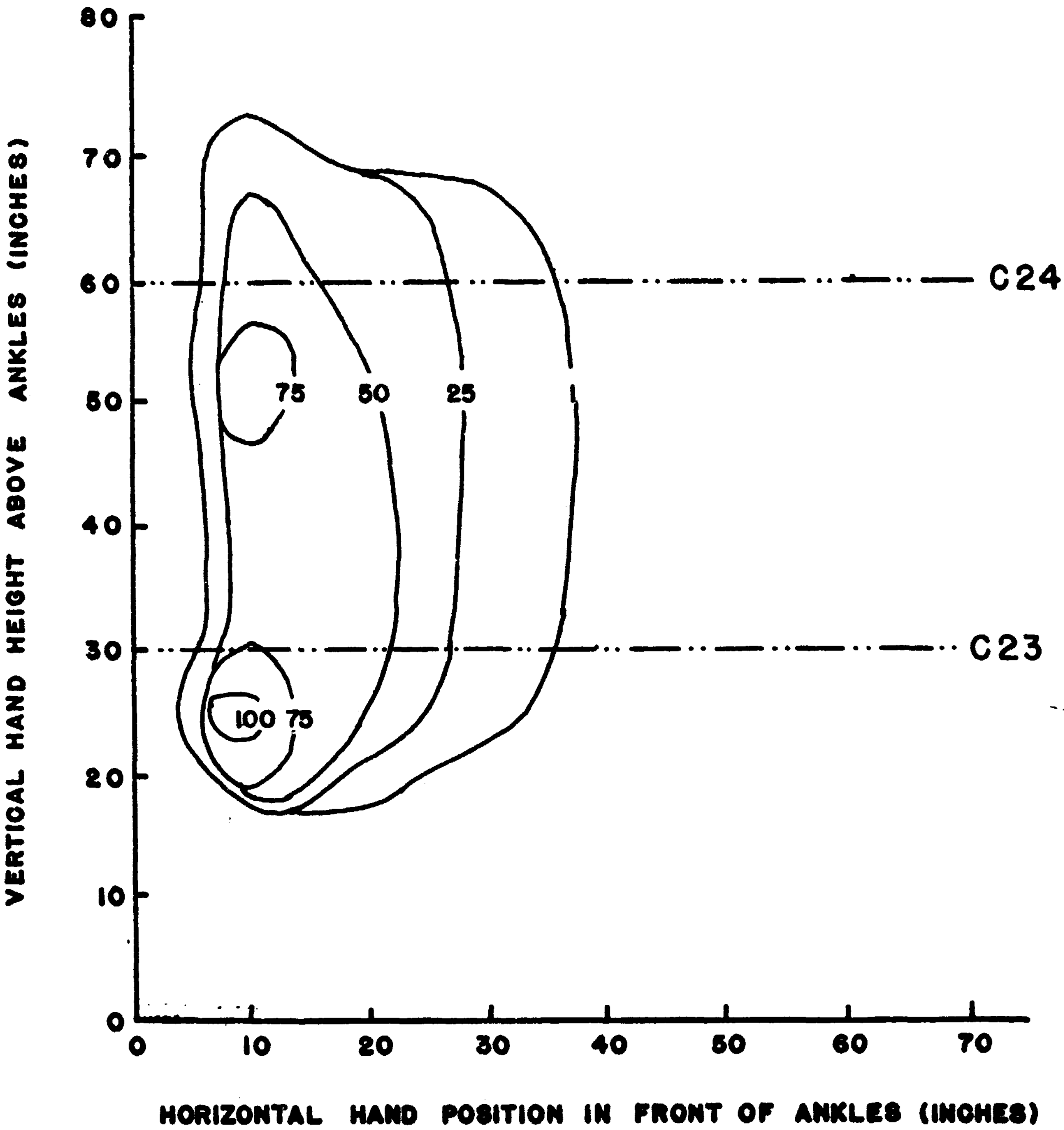
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 0.2 G

CLOTHING: SUITED

TASK: LIFTING



Space Suited Two-Handed Force Predictions

during

Pulling

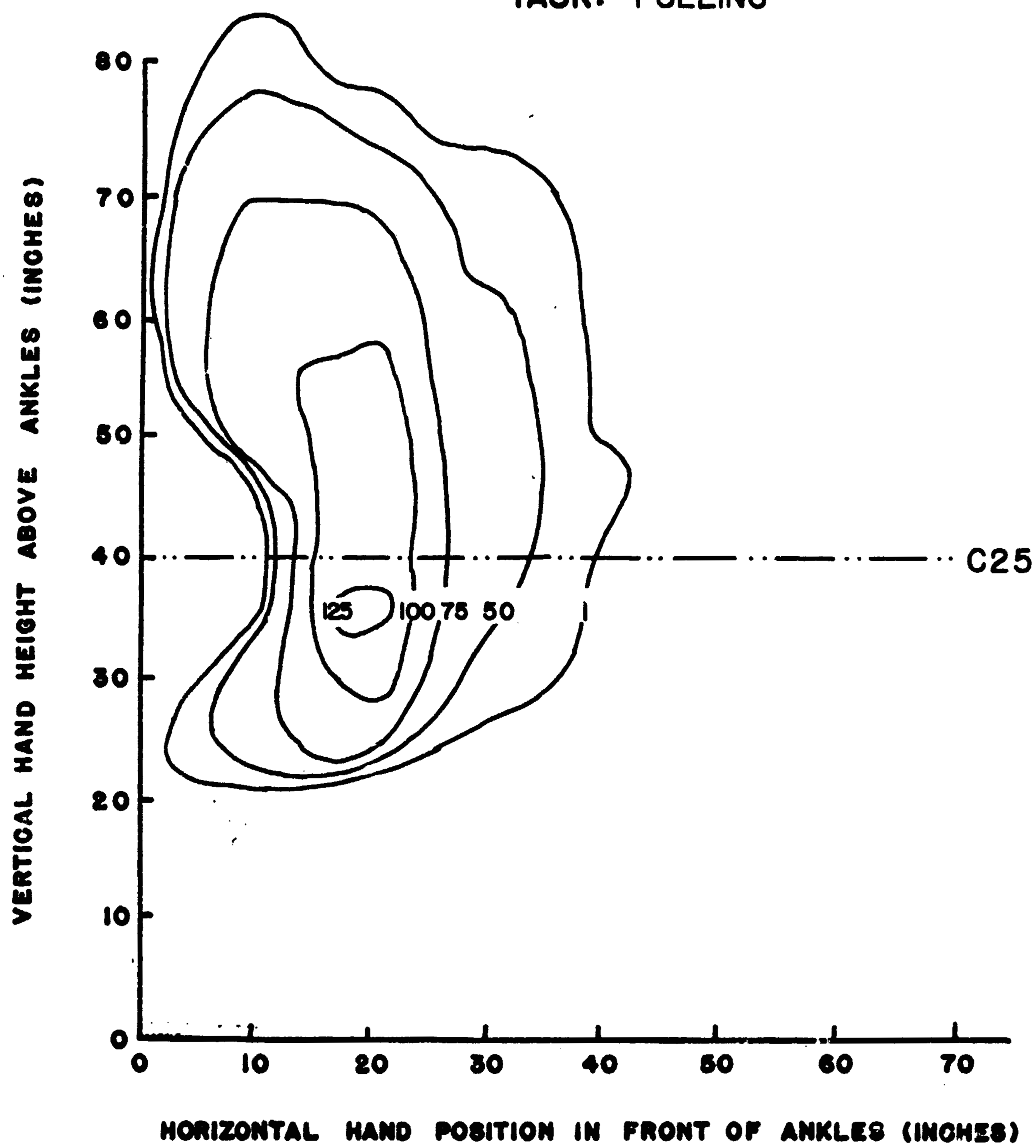
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 1.0 G

CLOTHING: SUITED

TASK: PULLING



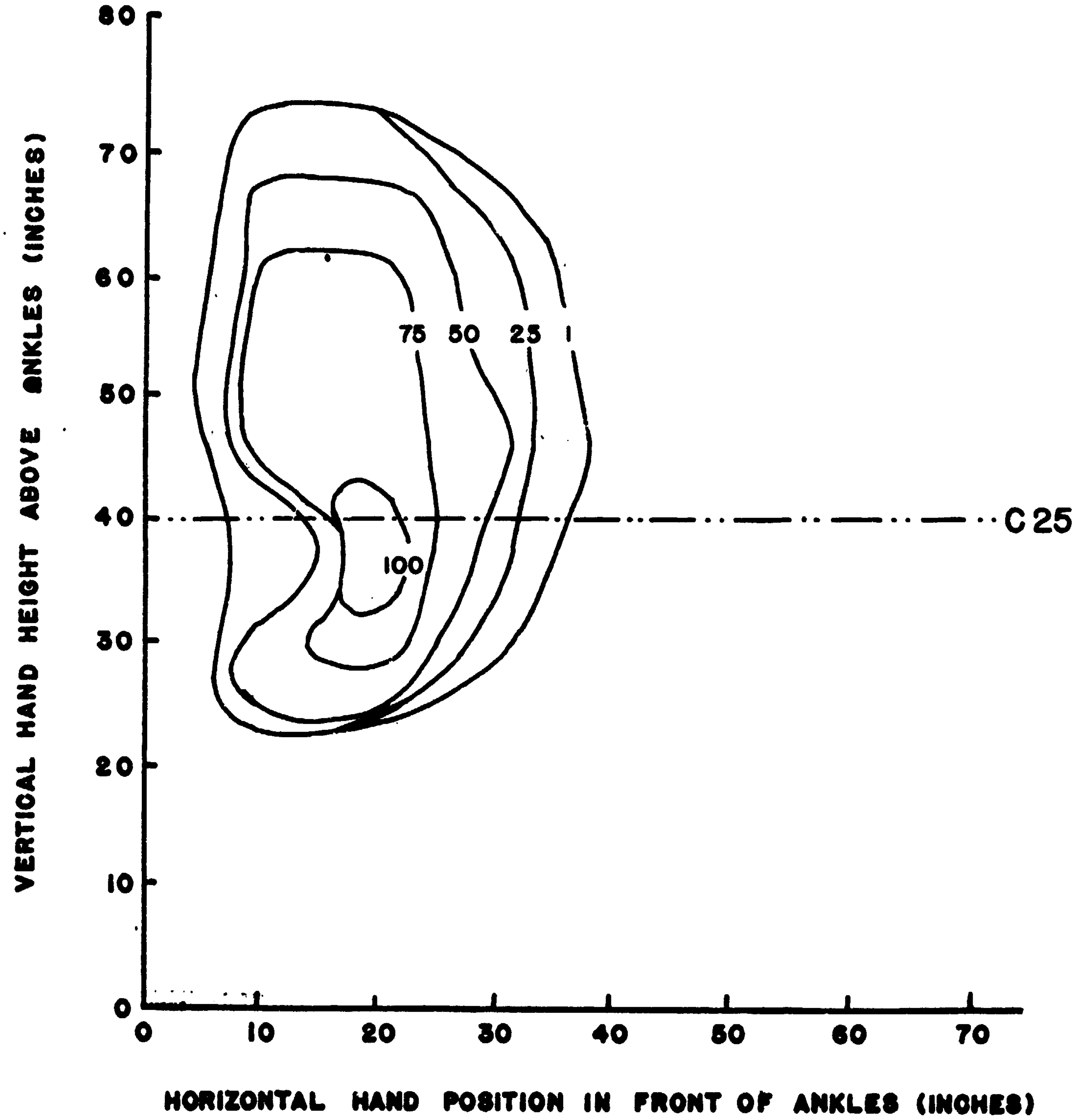
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 1.0G

CLOTHING: SUITED

TASK: PULLING



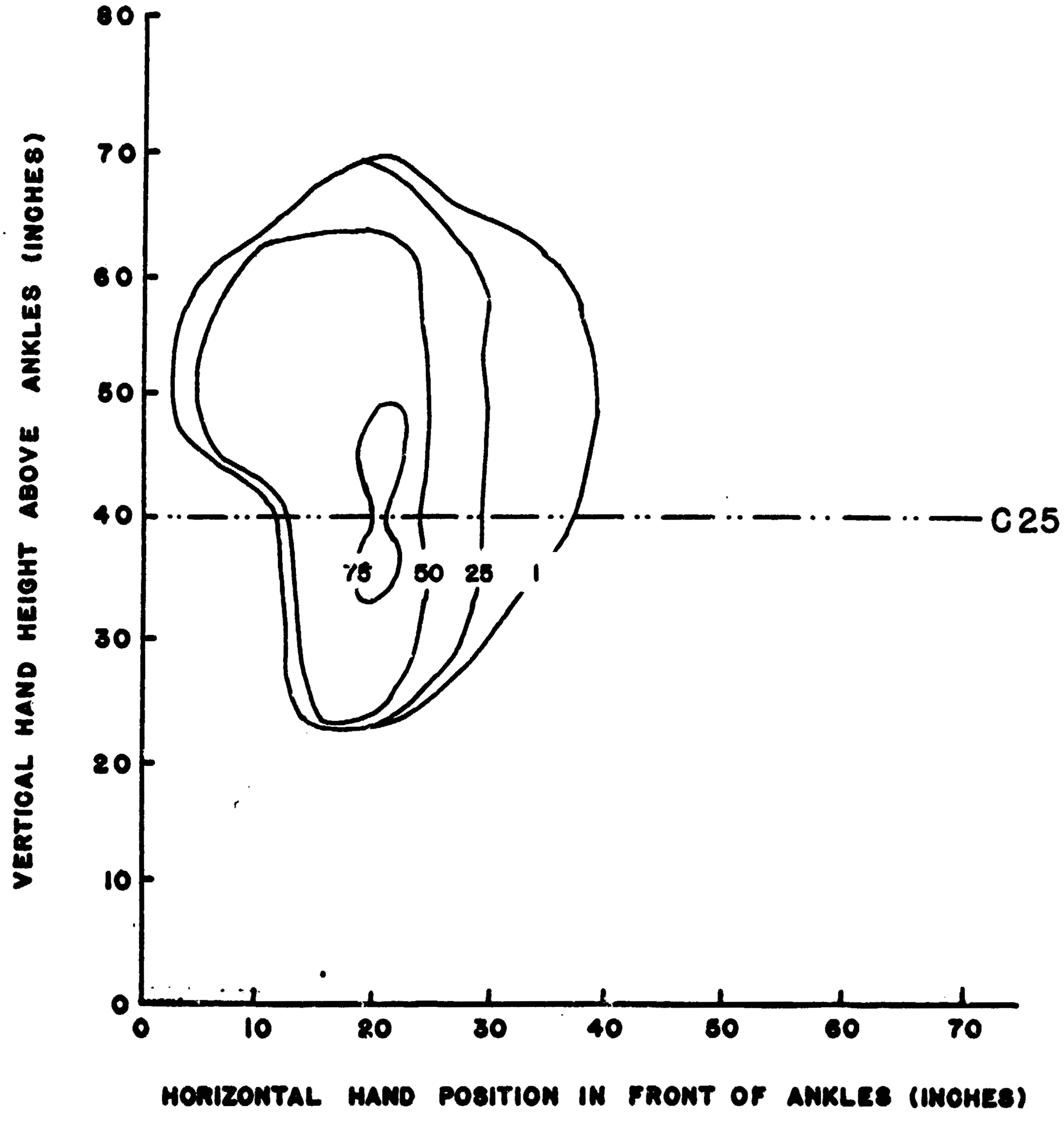
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 1.0 G

CLOTHING: SUITED

TASK: PULLING



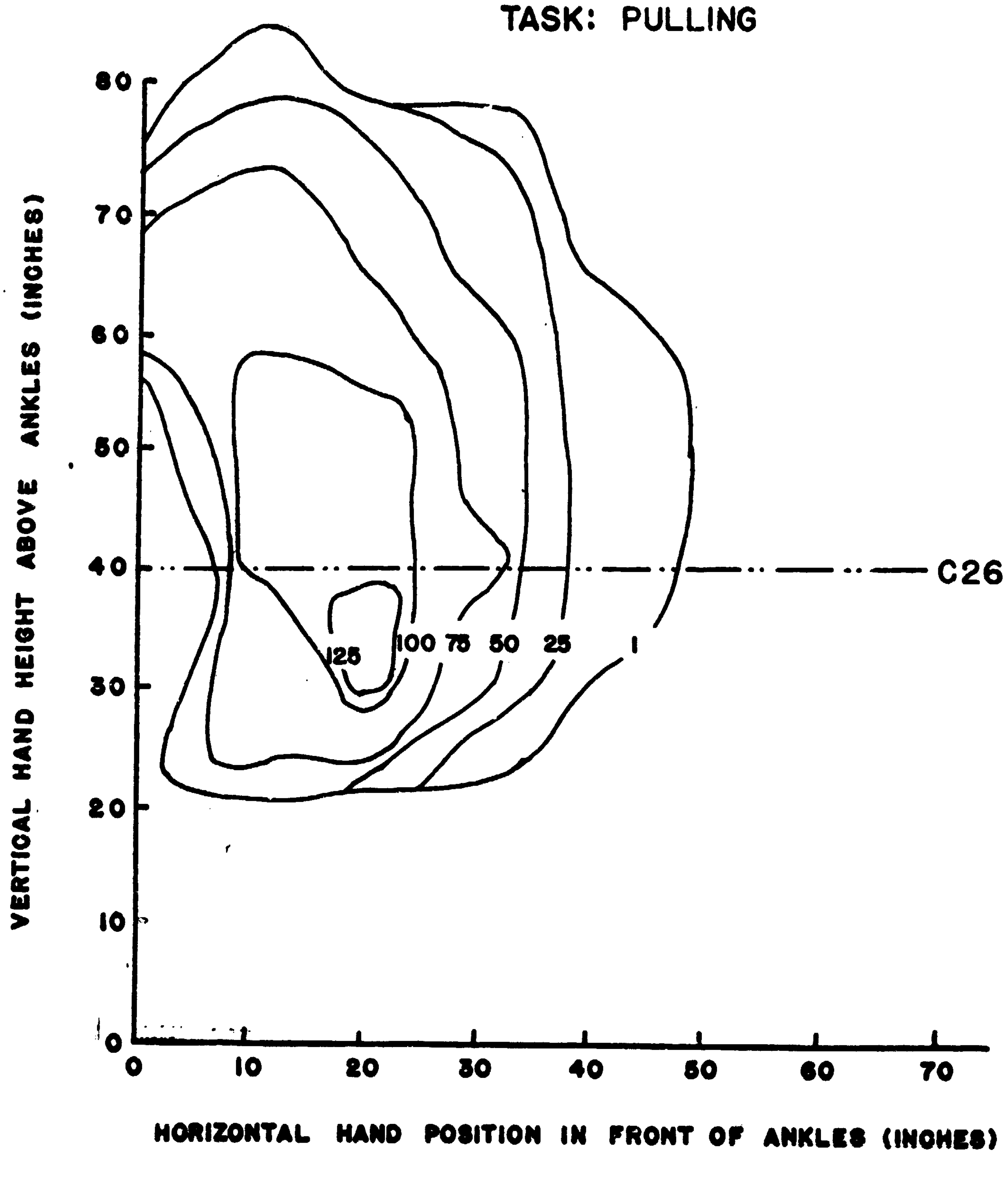
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 0.7G

CLOTHING: SUITED

TASK: PULLING



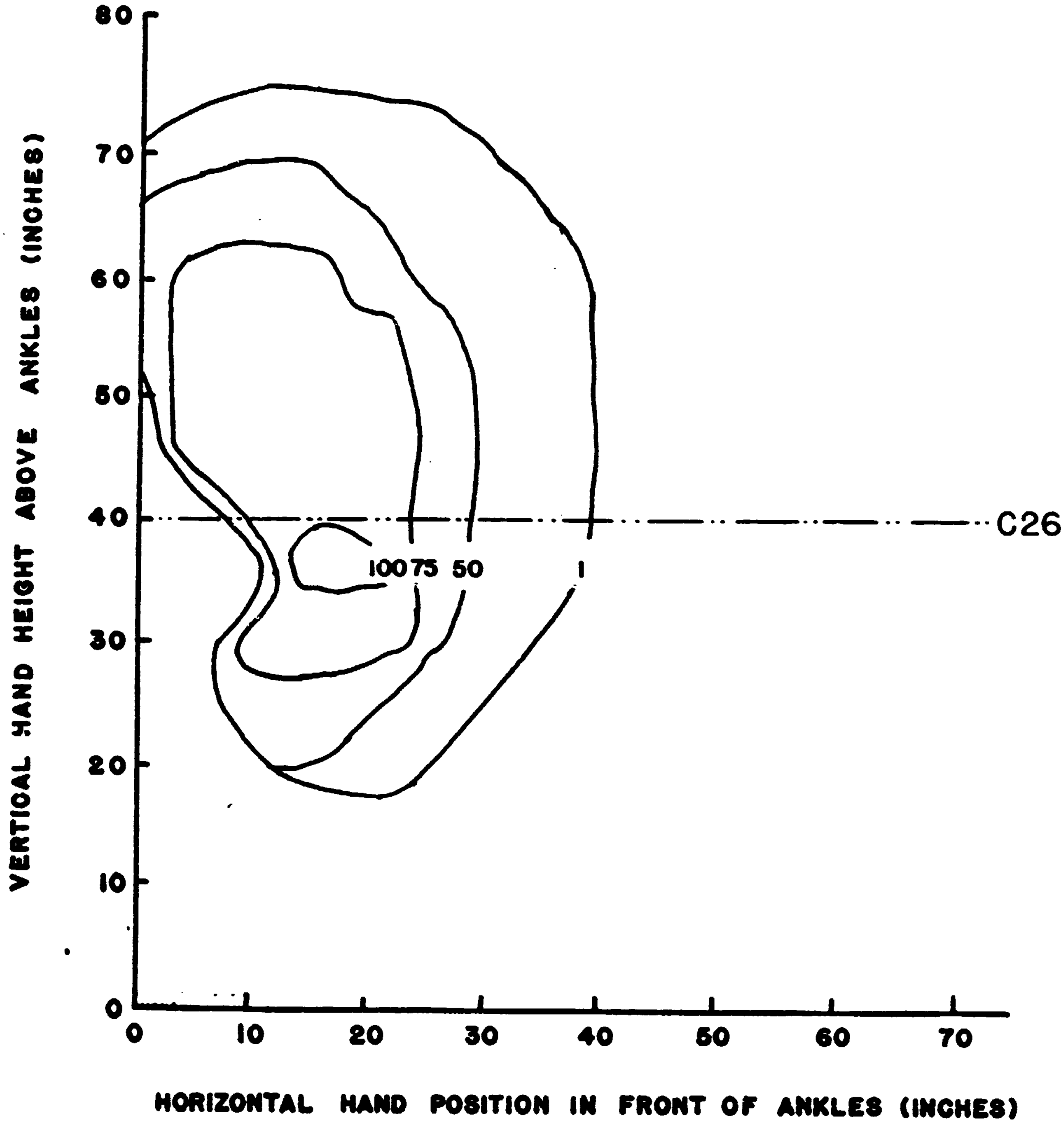
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 0.7G

CLOTHING: SUITED

TASK: PULLING



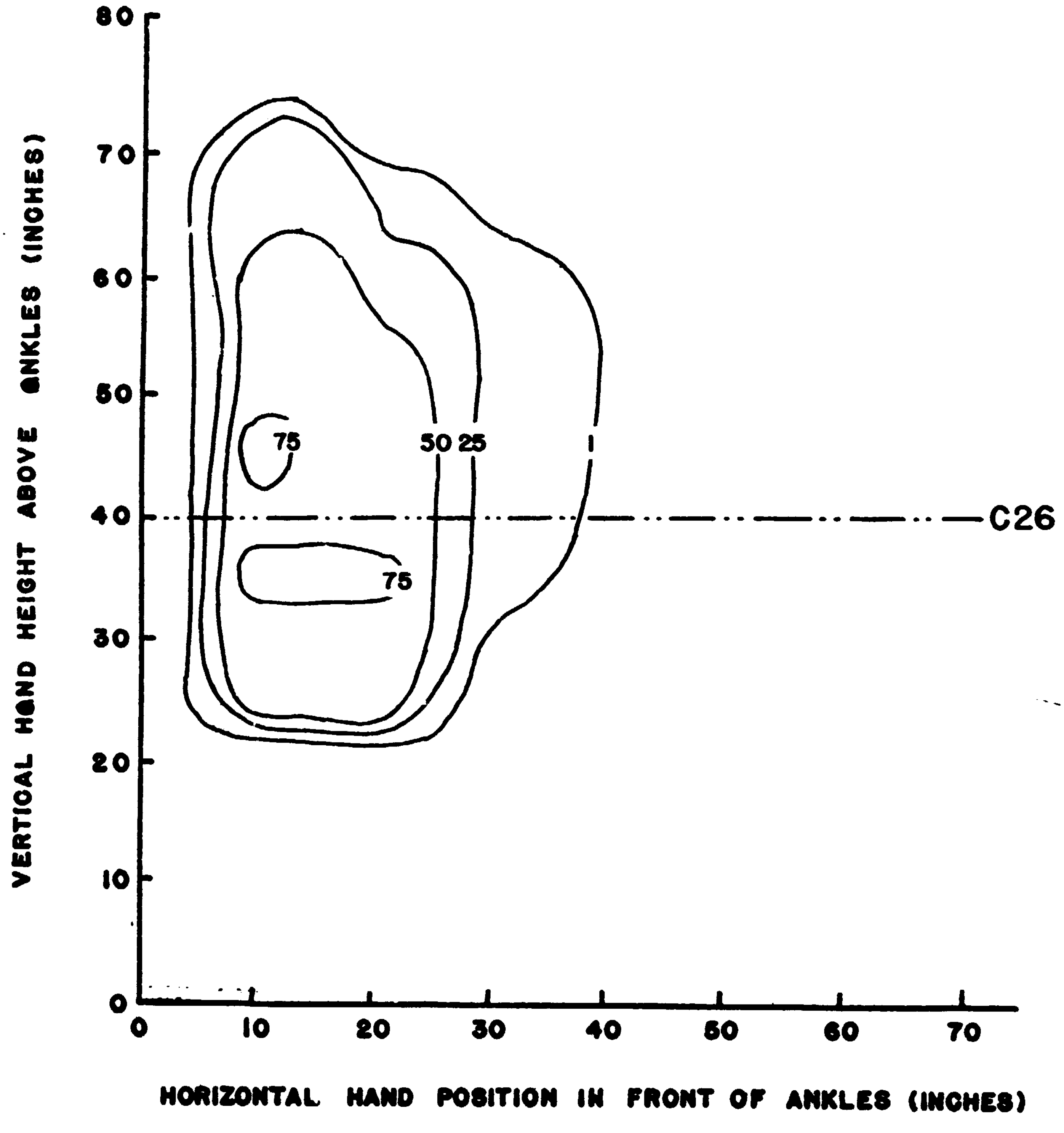
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 0.7 G

CLOTHING: SUITED

TASK: PULLING



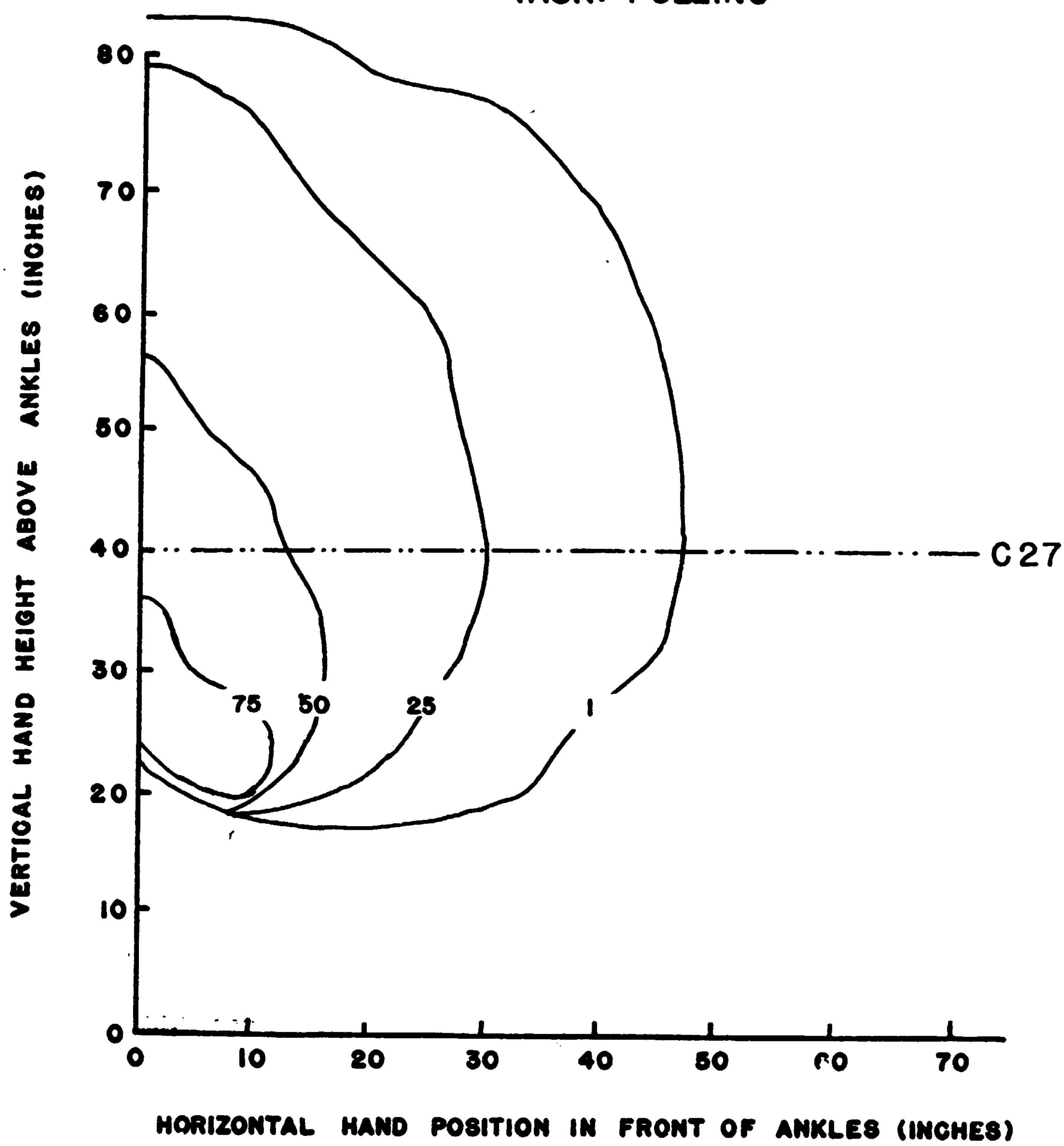
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 0.2G

CLOTHING: SUITED

TASK: PULLING



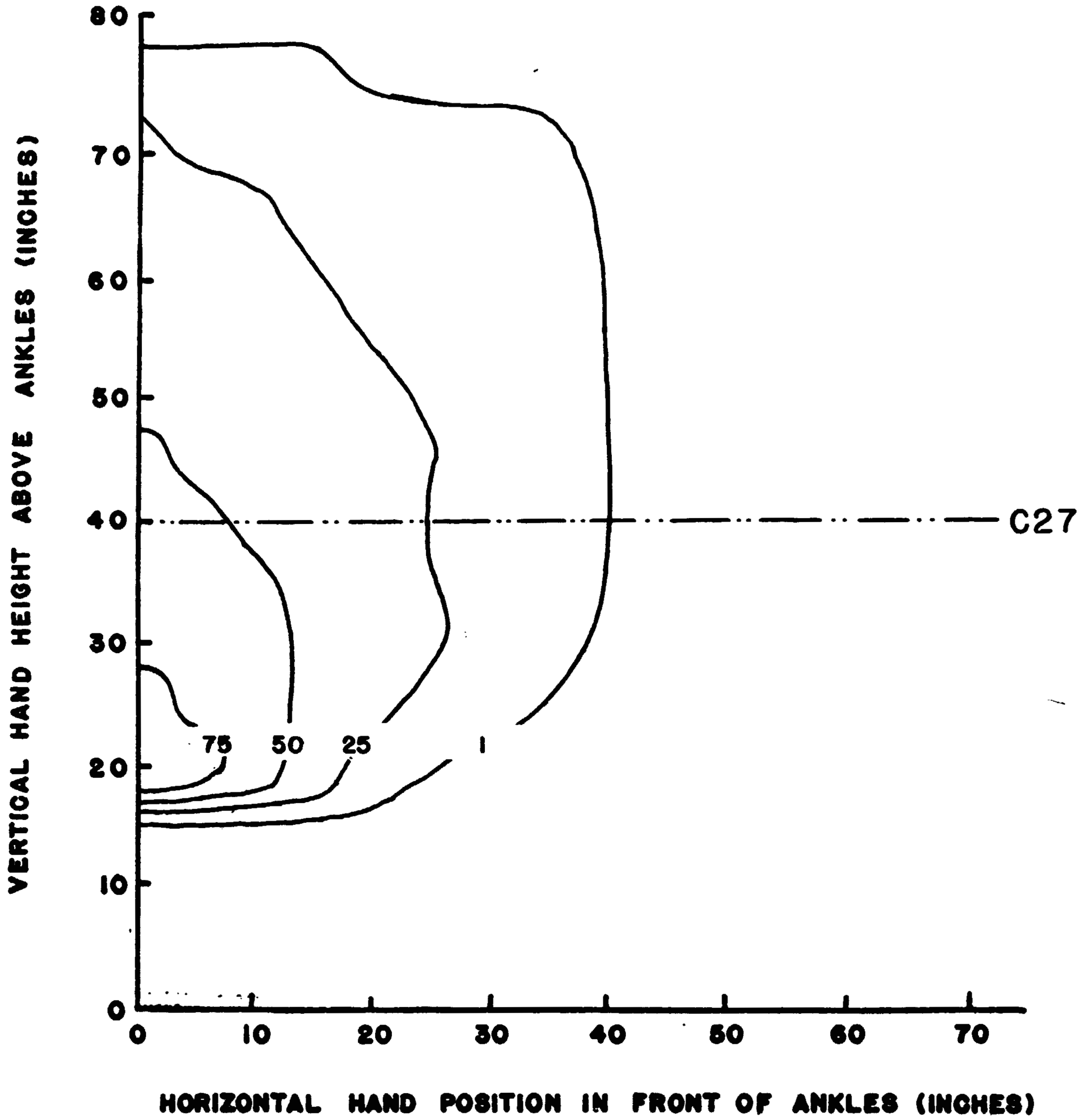
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 0.2 G

CLOTHING: SUITED

TASK: PULLING



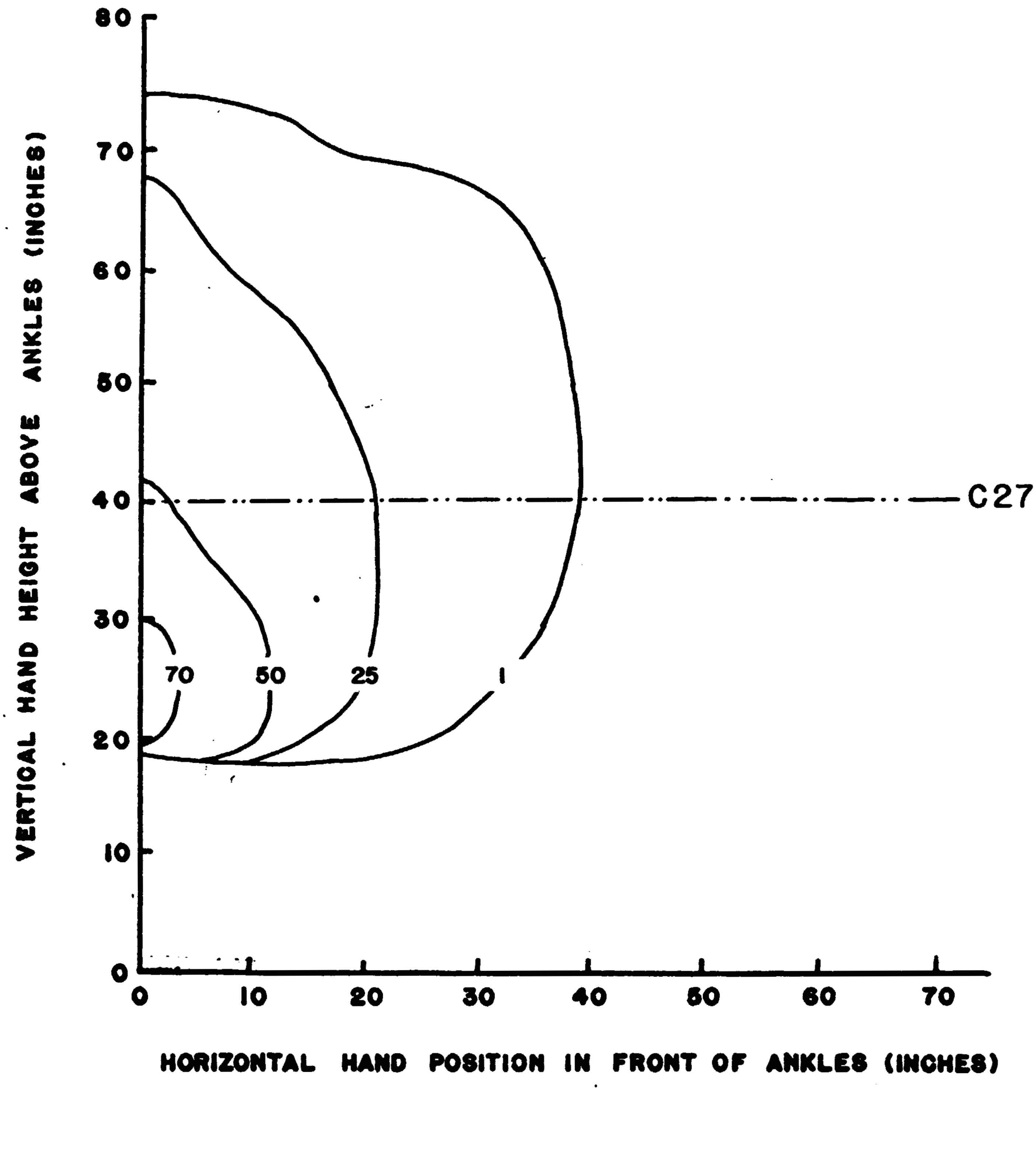
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 0.2 G

CLOTHING: SUITED

TASK: PULLING



Space Suited Two-Handed Force Predictions

during

Pushing

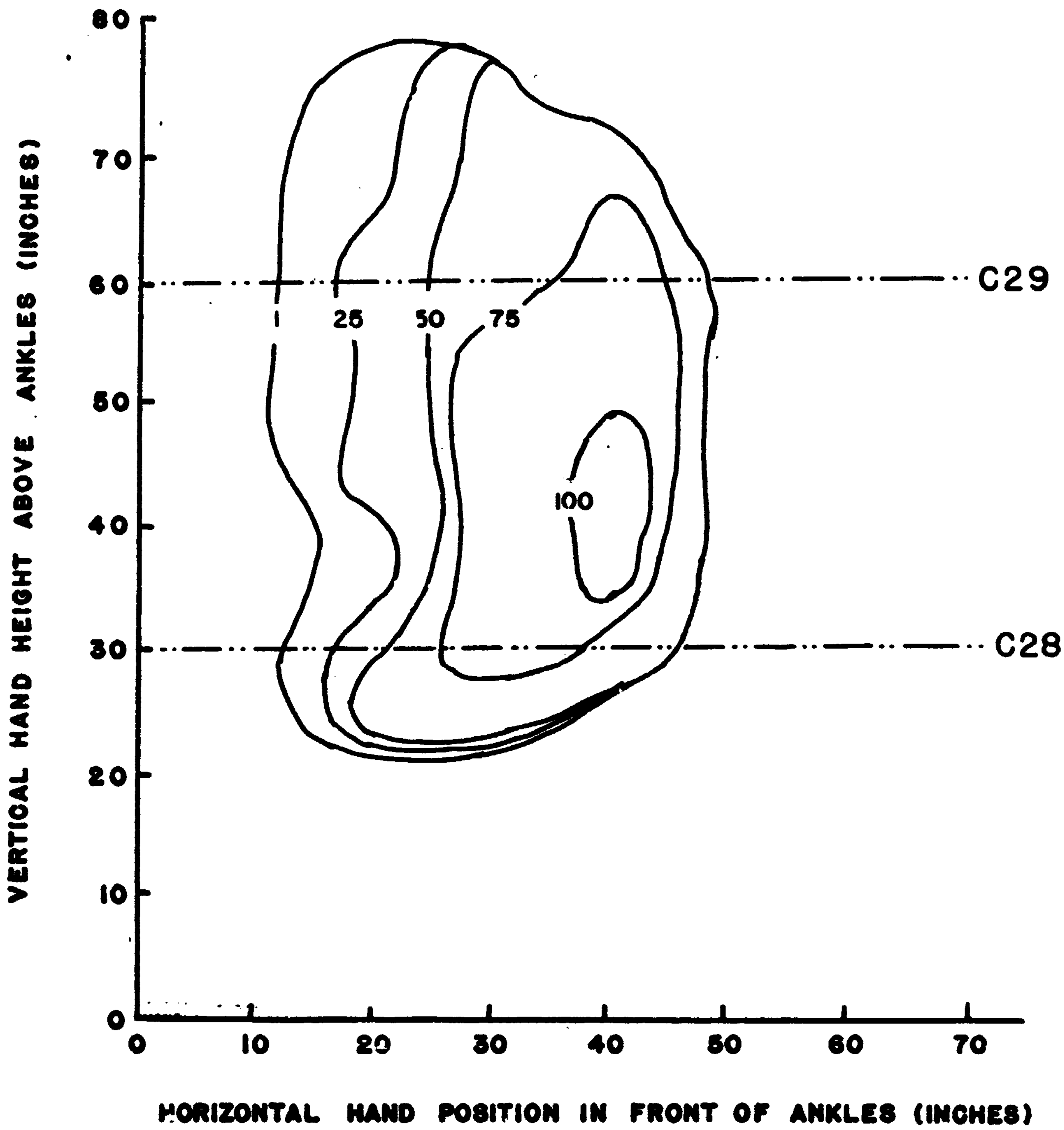
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5 %

GRAVITY: 1.0 G

CLOTHING: SUITED

TASK: PUSHING



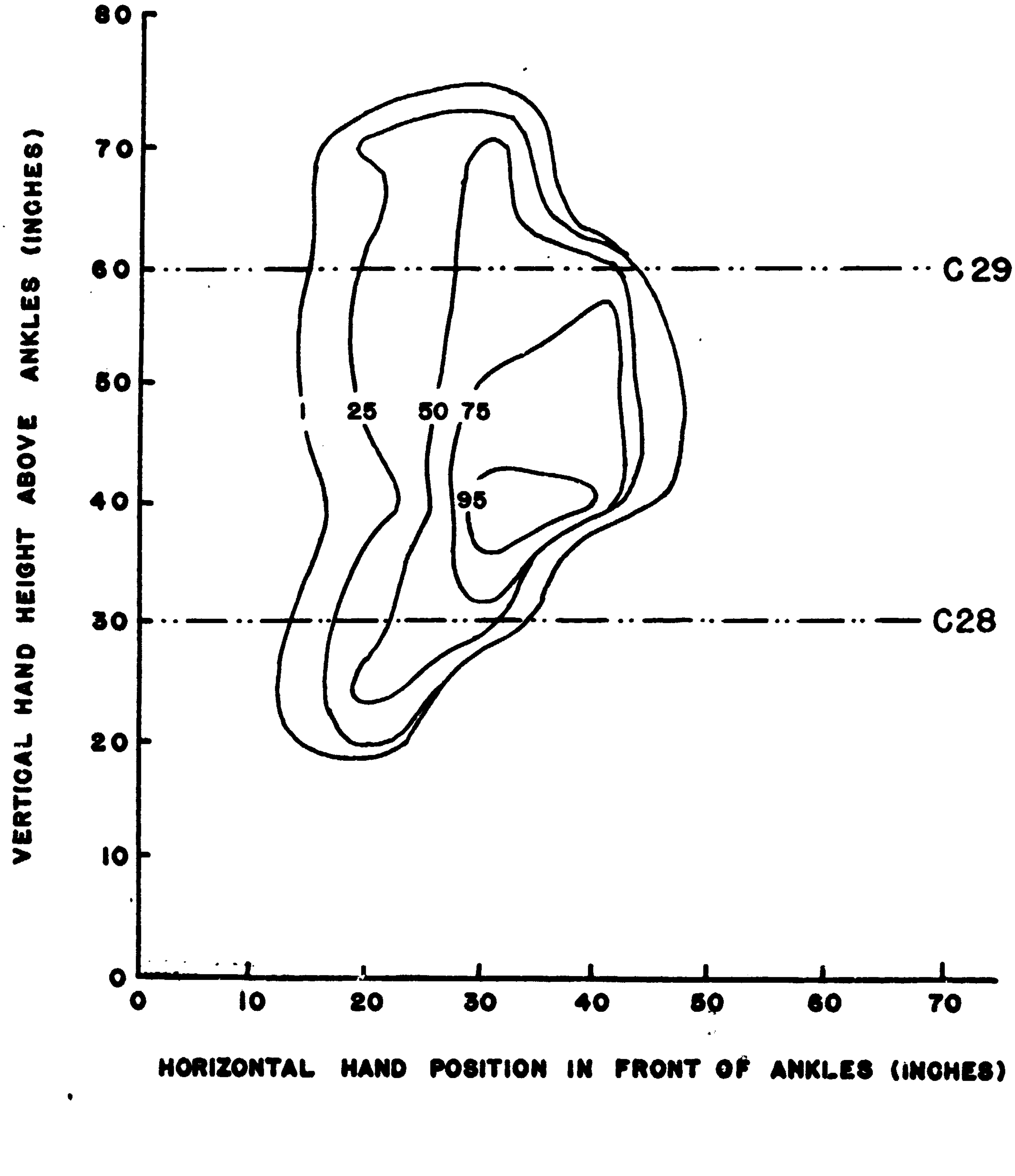
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 1.0 G

CLOTHING: SUITED

TASK: PUSHING



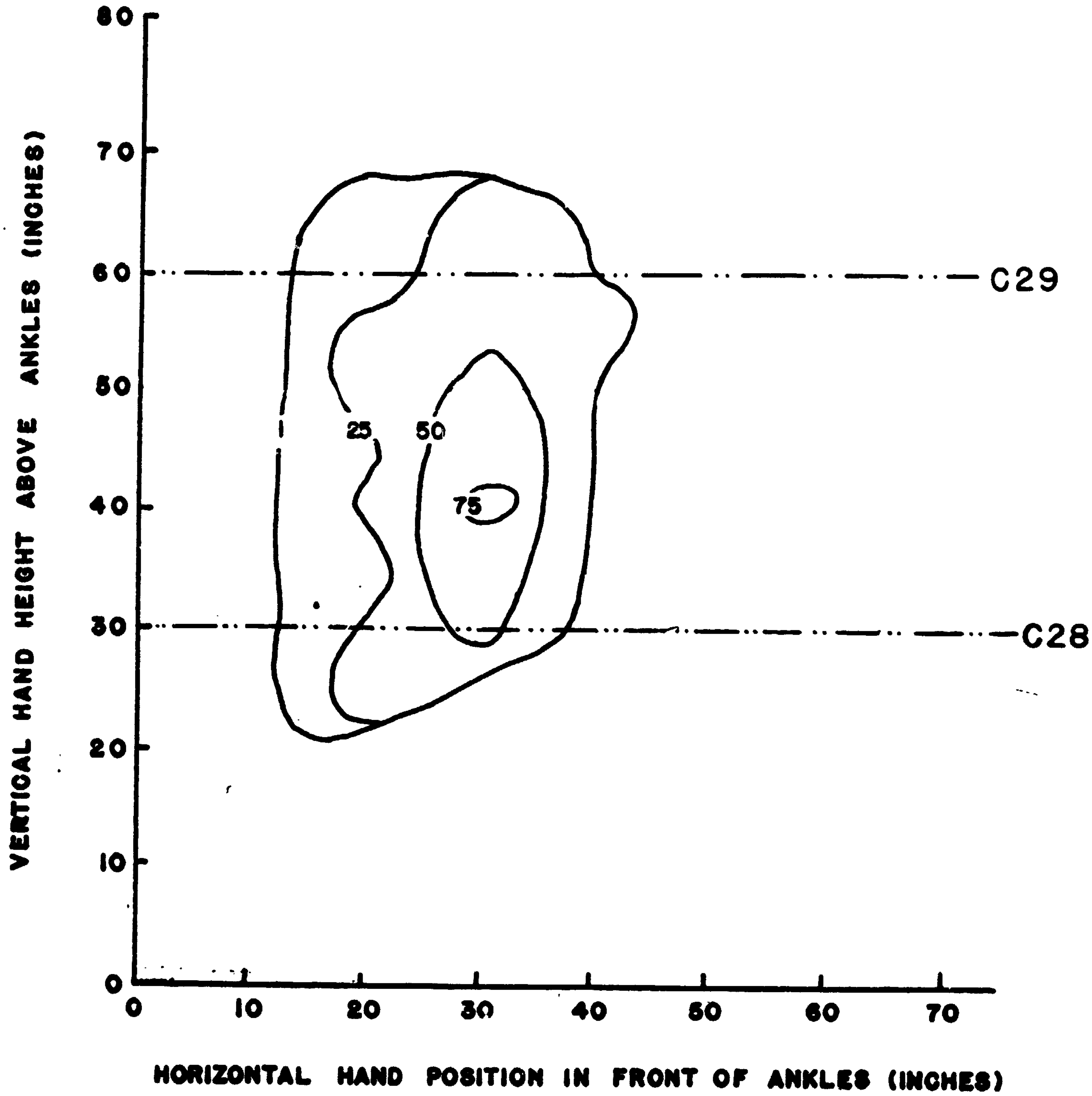
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 1.0 G

CLOTHING: SUITED

TASK: PUSHING



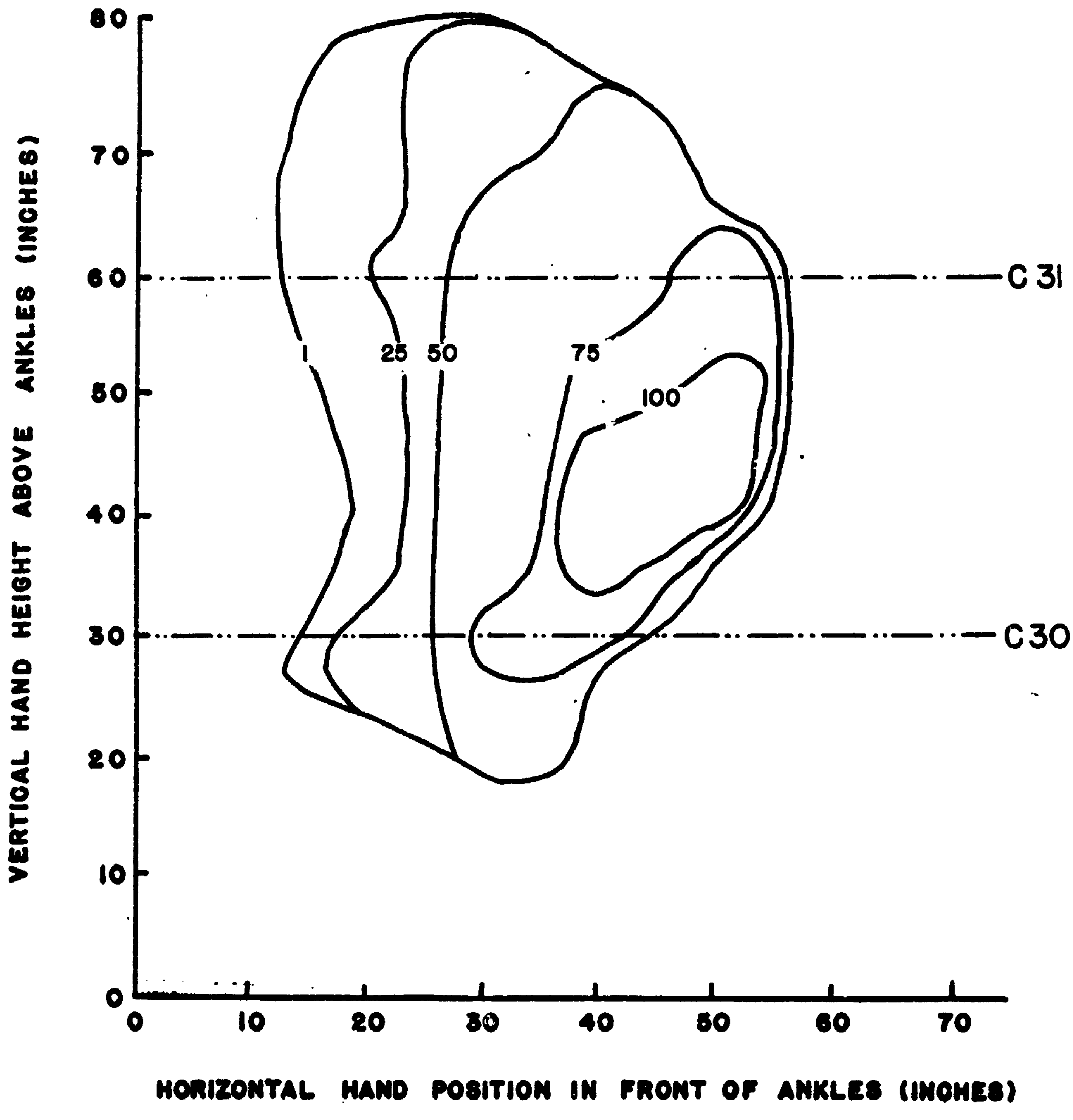
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5 %

GRAVITY: 0.7 G

CLOTHING: SUITED

TASK: PUSHING



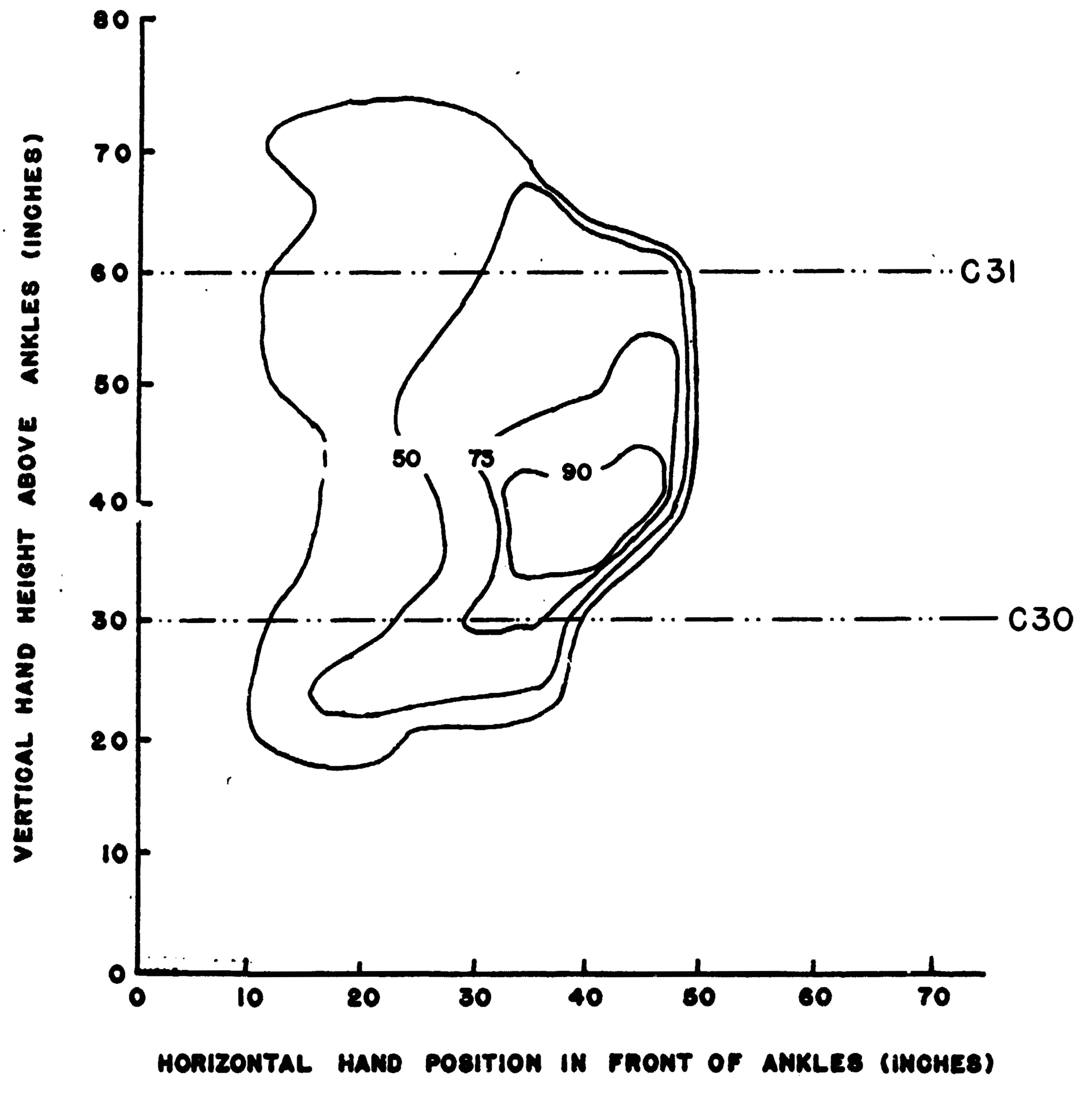
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 0.7G

CLOTHING: SUITED

TASK: PUSHING



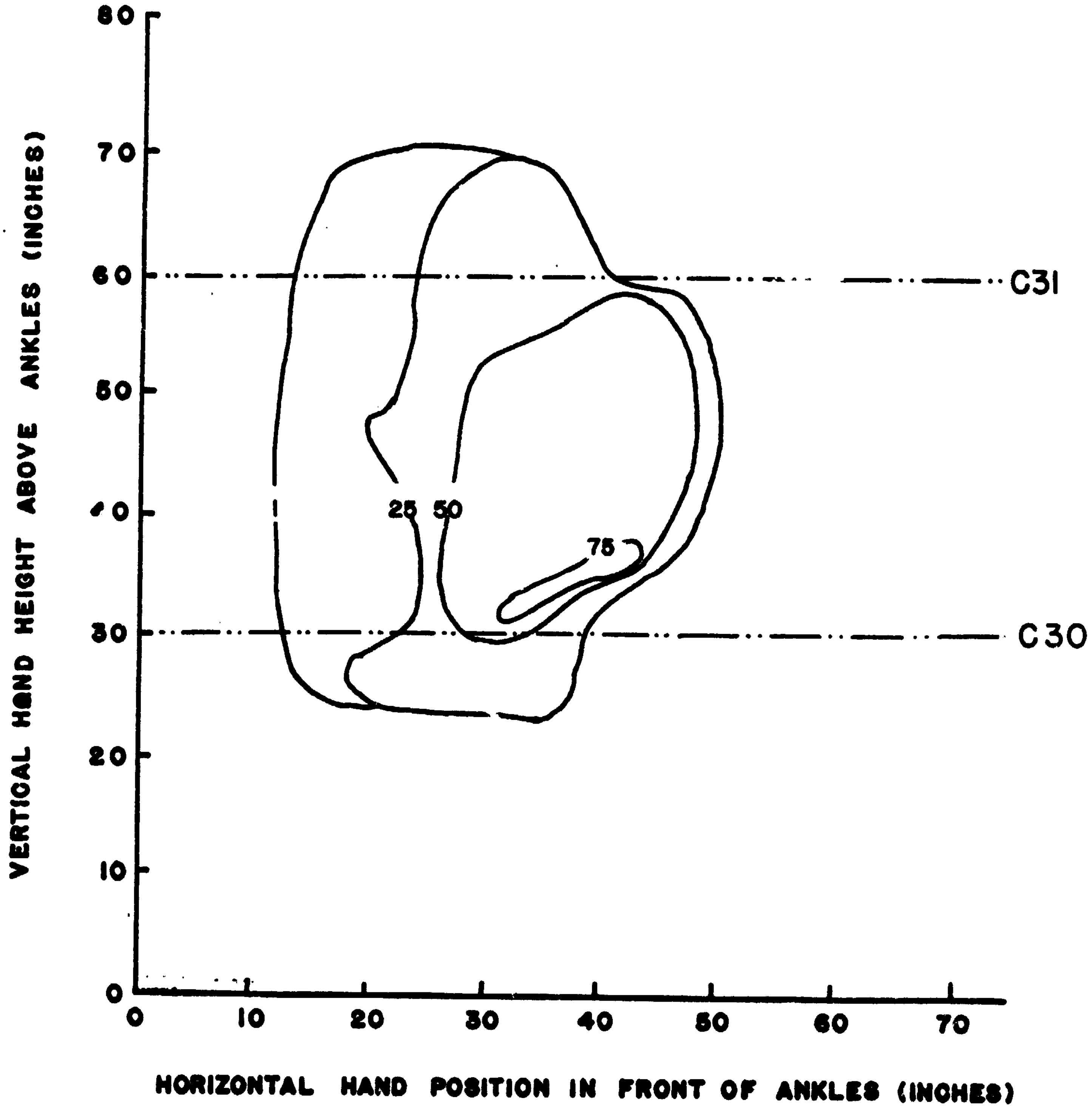
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 0.7G

CLOTHING: SUITED

TASK: PUSHING



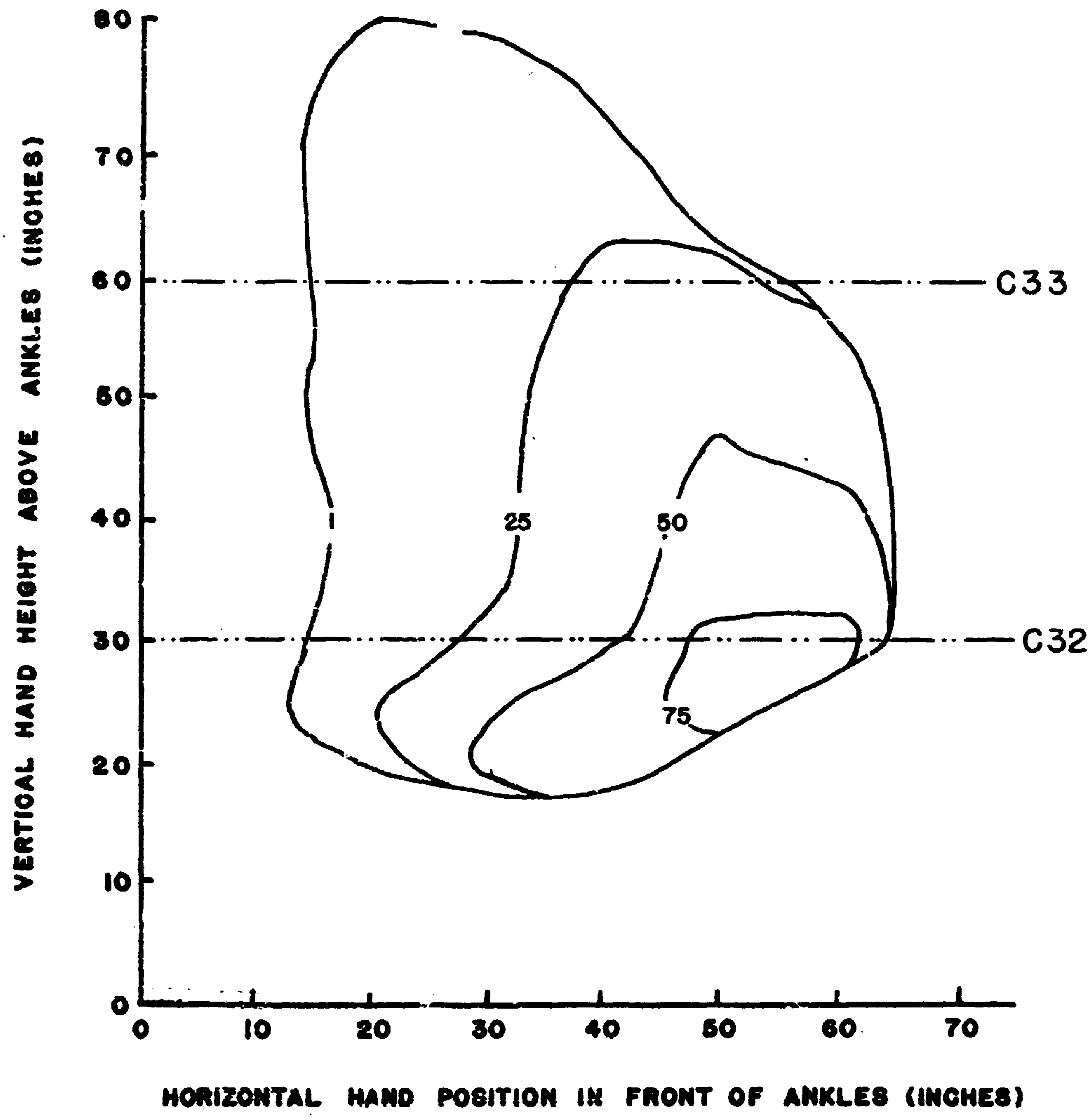
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 5%

GRAVITY: 0.2G

CLOTHING: SUITED

TASK: PUSHING



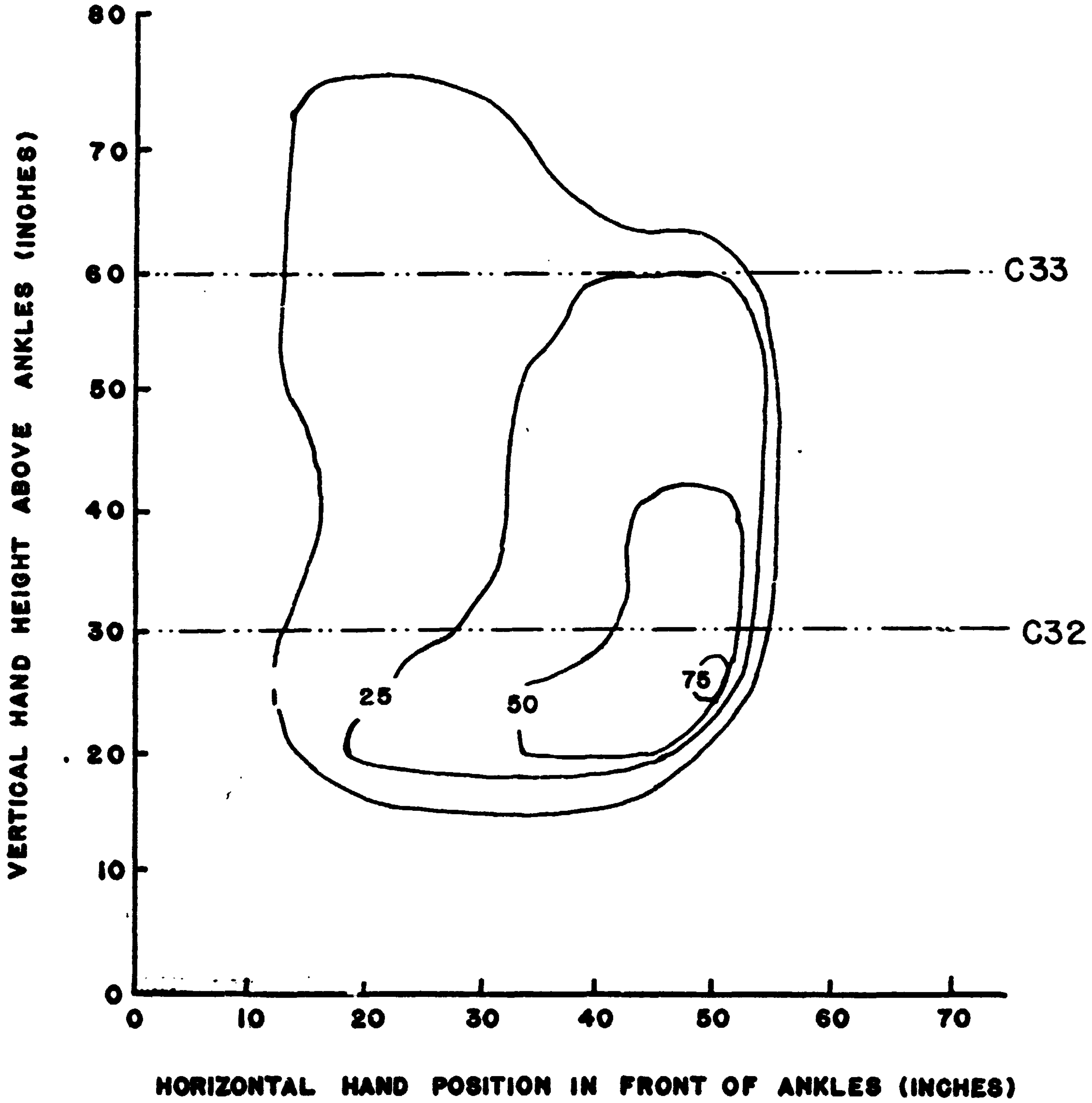
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 50%

GRAVITY: 0.2 G

CLOTHING: SUITED

TASK: PUSHING



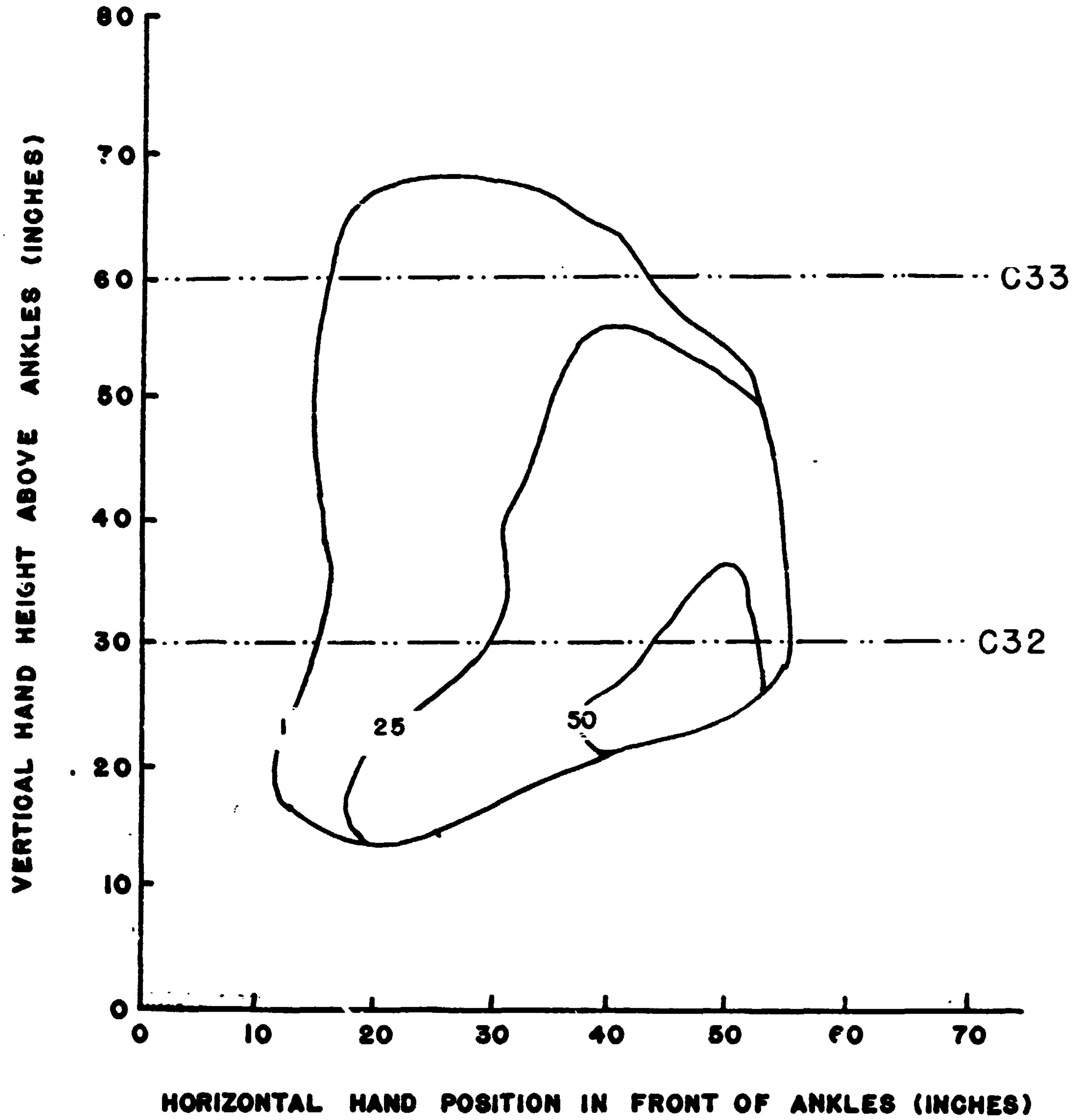
PREDICTED EQUAL HAND FORCE CAPABILITIES

POPULATION: 95%

GRAVITY: 0.2G

CLOTHING: SUITED

TASK: PUSHING



Summary of Suited, Two-handed Force Predictions

The two-handed force predictions depicted in the preceding graphs display some general effects, which are summarized in the following:

Factors affecting suited lifting predictions.

1. The greatest lifting force capability is predicted at slightly above knee height. For 1.0 g. conditions, maximum capability is located further in front of the person's ankles (i.e., he is required to lean forward more because of the backpack weight) as opposed to the 0.2 g. condition.

2. A large decrease in lifting force capability results if the hands are required to be more than 20 horizontal inches in front of the ankles.

3. In general, the vertical hand height (between 30 and 60 inches) does not greatly affect the lifting force predictions.

4. Reducing the gravity from 1.0 g. to 0.2 g. increases the lifting strength by an average of 20%, allows the average man to reach and lift one pound six inches lower, and increases the horizontal reach and lift capability by three inches for both

the average and larger/stronger men. This is because the reduced gravity allows the person to squat and lean forward more than in 1.0 g. conditions, due to the backpack weight reduction demanding less leg and low back strength. The vertical reach and lift height is not affected by gravity, since it is primarily dependent upon the range-of-motion restrictions provided by the suit.

5. The change from a smaller/weaker man to a larger/stronger man results in doubled lifting force capabilities. This effect appears to be due to a combination of problems related to size and strength. First the smaller/lighter weight individual, when required to reach out and lift, cannot achieve as many "good" body positions (i.e., he is often close to his balance limit, or he cannot achieve the higher muscular capability positions depicted in Appendix A). In addition, the articulation torques introduced by the suit and backpack reduce the weaker person's strength proportionally more than the stronger person's, thus leaving less strength to be used in the lifting activity.

<u>Factors affecting suited pulling force predictions.</u>

1. For both 1.0 and 0.7 g. conditions, the greatest predicted pulling capability is achieved when the hands are about hip height and 20 horizontal inches in front of the ankles. When the gravity is reduced to 0.2 g., this maximum pull position moves to almost over the ankles and becomes slightly lower (mid-thigh), thus allowing the person to squat back further to take advantage of the counterbalancing effect of his backpack weight. When in the higher g. loads, his leg strength is not sufficient to allow him to squat and lean back when wearing the backpack. Once again, from the safety standpoint, it must be mentioned that the "squat and lean back" position subjects the person to the possibility of falling backwards (i.e., either the feet slide forward suddenly or the object being pulled releases quickly). The more vertical the hand position, the more erect the person can be, and thus the better the chance of recovering his body balance by quickly moving one foot backwards.

2. Reducing gravity from 1.0 to 0.7 g.'s has only a slight effect on the pulling capability predictions but the 0.2 g. condition reduces both the average and larger/stronger males' general pulling capabilities by about 25%. The smaller/weaker individual's

pulling capability does not appear to be greatly affected by the reduced gravity.

3. The smaller/weaker man has about 40% less predicted pulling capacity than the larger/stronger man for the 1.0 and 0.7 g. conditions. The anthropometry variable does not appear to be of much effect on pulling capability in 0.2 g.'s, providing the person can reach the object of interest.

4. In general, the smaller/weaker man has 10 less inches of reach and pull height than the larger/stronger man.

Factors affecting suited push force predictions.

1. The hand position required to achieve the maximum push is very much dependent upon the gravity conditions. For 1.0 g., the maximum is achieved with the hands at about 35 inches horizontal and 40 inches vertical to the ankles. This area progressively shifts away from the ankles (i.e., to 50 inches horizontal for 0.2 g.'s), and lowers (i.e., to 25 inches vertical for 0.2 g.'s). This shift appears to be due to the person being more capable of pushing when in a greater "lean forward" position with reduced gravity conditions. Once again, it must be mentioned that the lower body configurations when pushing increases the possibility of a forward

fall if either the feet or object suddenly shifts position. Hence a higher hand position should be designated, where force requirements allow.

2. A gravity of 0.2 g.'s results in the maximum pushing force capabilities being reduced by an average of about 25% from that of the 1.0 g. capabilities.

3. Very poor pushing capabilities are the result of hand positions being above the shoulders and less than 20 inches in front of the ankles.

4. The smaller/weaker man averages 25% less predicted pushing capability than the larger/stronger man.

5. The reach/push area is about 10 inches less in the horizontal dimension for the smaller/weaker man than for that of the larger/stronger man. The vertical reach/push dimension is about 12 inches less for the smaller/weaker man than for that of the larger/stronger man.

Section V

Summary

This section summarizes some of the general strength problems associated with two-handed lifting, pushing, and pulling activities depicted in the preceding simulation results. In addition, limitations of the present model are briefly presented to serve as a basis for defining future strength model requirements.

An Overview of Two-Handed Strength Modelling

Concepts of mechanics and anatomy are equally well developed to provide a basis for modelling the human strength problem. Furthermore, the digital computer provides the computational capacity to solve the complex analytical expressions necessary to depict the stress-strain relationships of the musculoskeletal system.

This manual is the result of one group's four-year effort to develop a biomechanical model of the volitional human force problem. The resulting model has been documented elsewhere (Chaffin, 1969, and Chaffin and Baker, 1970), and is only briefly described in Section II, except for the specific modifications necessary to depict space suited and reduced gravity conditions.

The biomechanical strength model predicts the volitional force that a person can produce with both hands when statically and symmetrically loading the body in the sagittal plane. In determining the hand force capabilities, the model systematically varies the body configuration to ascertain the configuration which would allow a statistically-described size and strength person to exert his greatest hand force. Limits to a person's hand forces are provided by, 1) volitional muscle strengths for specific types of exertions, 2) allowable compressive forces for the lumbosacral disc, and 3) body balance maintenance. In addition to predicting hand force capabilities, the model outputs a prediction of the horizontal and vertical dimensions of the work envelope required by the largest (5%) man when attempting to exert the predicted hand forces.

Some General Observations Regarding Two-Handed Force Variations

The following general observations are made to depict some of the design trade-offs that exist in regard to two-handed force capabilities, and in particular to situations with and without the A7L space suit and backpack.

1. The greatest lifting capability is when the hands are about knee height.
2. The space suit and backpack reduce the average lifting capability by about 30%.

3. The space suit and backpack do <u>not</u> significantly change the average pushing force capabilities for given conditions of gravity, population anthropometry and feasible reach positions. However, the suited reach/push area is reduced, (see 7 below).

4. The space suit and backpack slightly reduce the average pulling capabilities in 1.0 and 0.7 g. conditions. In the reduced 0.2 g. condition, however, the backpack weight assists the person, and thus increases the suited pulling force capability.

5. The greatest pulling hand forces are achieved when the hands are only slightly in front of the ankles and at mid-thigh height.

6. The greatest pushing hand forces are achieved with the hands at hip height for 1.0 and 0.7 g.'s, and at knee height for 0.2 g. conditions. To achieve the maximum, it also requires that the subject "lean into" the act by having his hands from 35 to 50 inches in front of his ankles, depending upon gravity and suit conditions.

7. The space suit and backpack reduce the area in which a person can reach/lift, push, and pull within the following general boundaries:

A. The lower boundary is about knee height rather than ankle height.

B. The near-body boundary is increased to an average of eight inches in front of the ankles.

C. The horizontal extreme reach boundary is reduced from an average of 49 inches to 40 inches.

D. The upper vertical reach boundary is reduced from an average of 79 inches in shirt-sleeves to an average of 75 inches.

Future Strength Modelling

The limitations of the present model to those conditions where a person is standing and attempting to push, pull or lift an object located directly in front of him are restrictive. Even so, the trade-offs depicted by the equal hand force graphs are believed to be directly useful for mission planning and hardware specification.

The basic techniques and human musculoskeletal data are now available to develop more comprehensive biomechanical models. As an example, these researchers are currently developing a biomechanical strength prediction which would allow a person to ascertain the specific effects of various restraint systems and body positions on a person's one and two-handed force capabilities when in zero gravity conditions.

The two-handed force prediction results depicted in this document represent only one manner in which the biomechanical model can be used to enhance future man/machine and mission design. Another use of the model requires the designer to directly input to the computer his specific task specifications (e.g., population size and strength, hand positions, and tasks). Simple card formats have been worked out for this purpose.[1] When using the program directly, more comprehensive design data is obtained. Specifically, the model lists for each input specified:

1. Maximum hand forces for three different body configurations. The body configurations are chosen to allow the highest hand forces possible, as compared to all other feasible body configurations.
2. Specific body configurations for the maximum hand force predictions (specified in body angles).
3. Work envelope dimensions, which define the area required for the large-strong (5%0 of the male population when exerting a maximum hand force.

The further development and validation of these models is a goal to which the Engineering Human Performance Laboratory at The University of Michigan is dedicated. It is believed that only through the use of models similar to the one used in this project will future designers be capable of optimizing man's performance prior to costly hardware commitments.

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[1] Dr. W. Feddersen, Chief of Behavioral Performance Laboratory, MSC, can supply a complete set of documentation for direct use of the model.

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APPENDIX A

Maximum Voluntary Torque Curves

This appendix depicts average changes in specific strengths due to different articulation angles. The strengths are stated in terms of maximum voluntary torque values. The shirt sleeve values are averages from:

*Clarke, H. H., Muscular Strength and Endurance in Man, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1966, pages 39-51.

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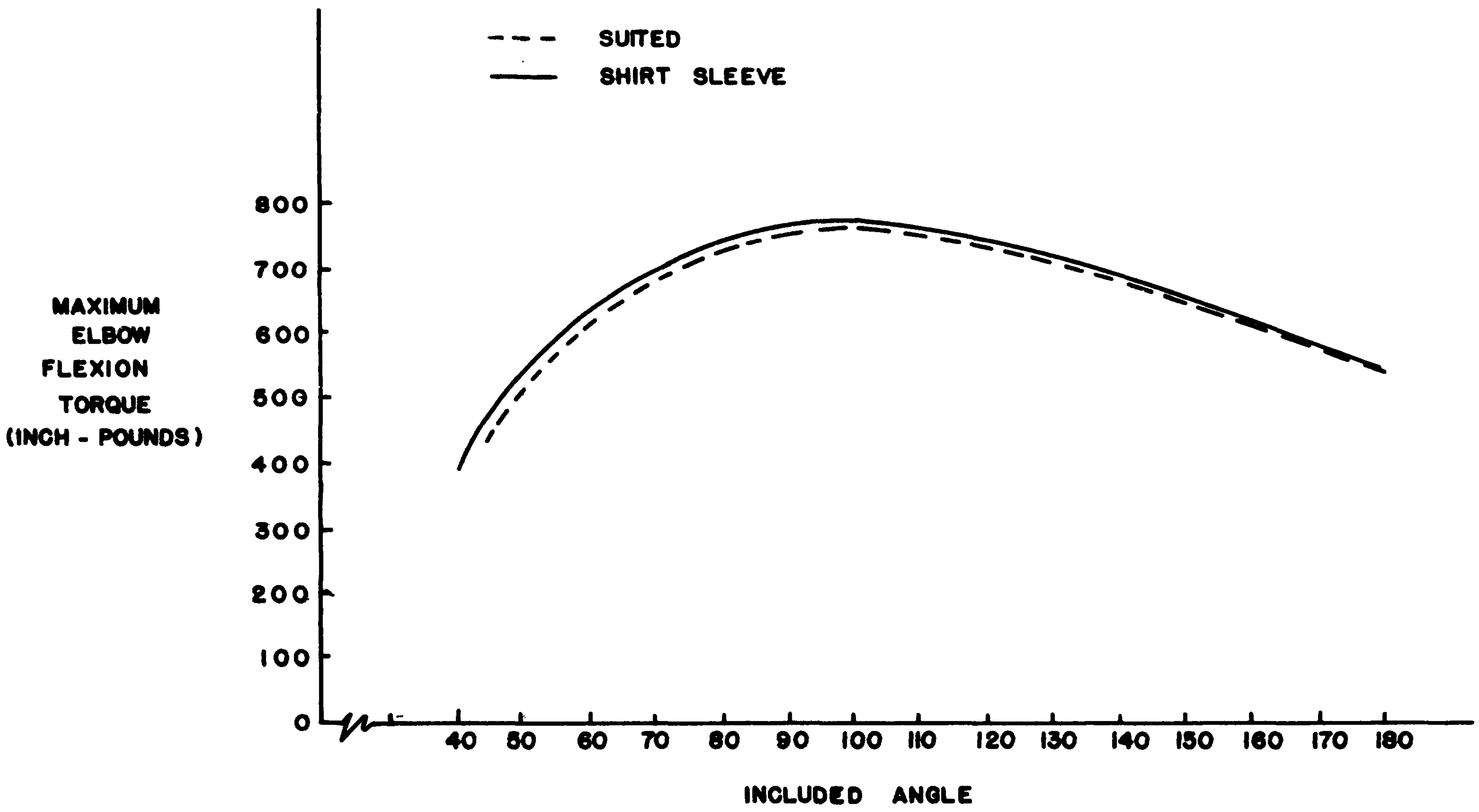
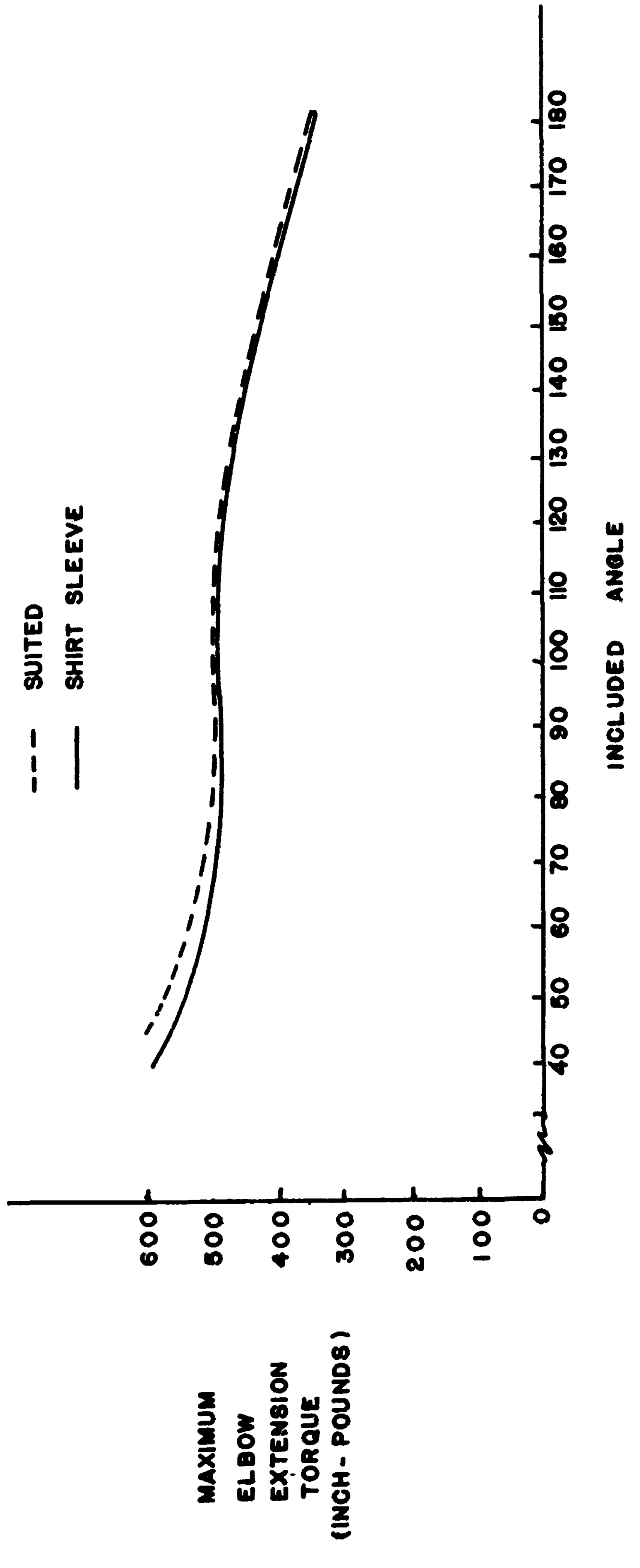
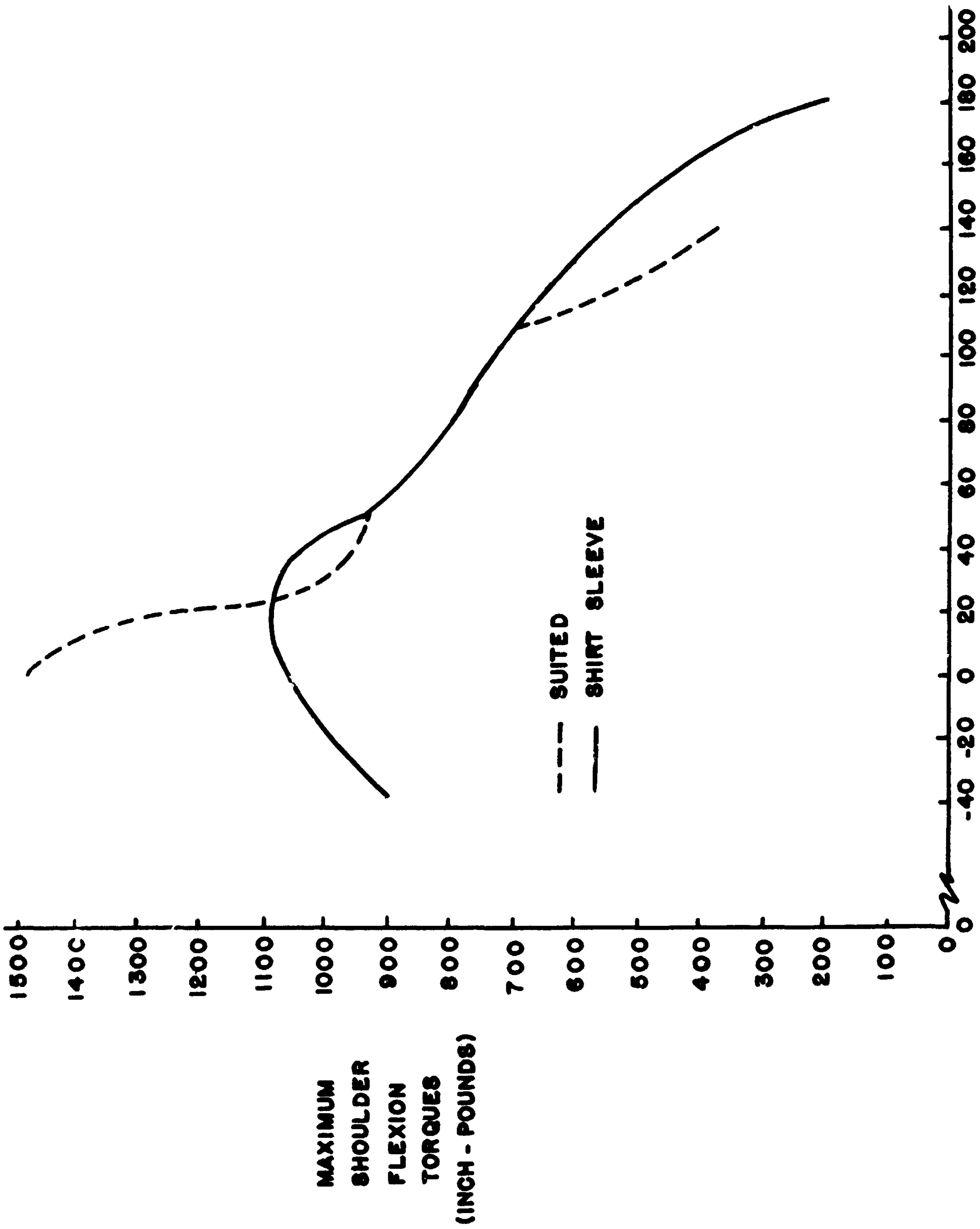
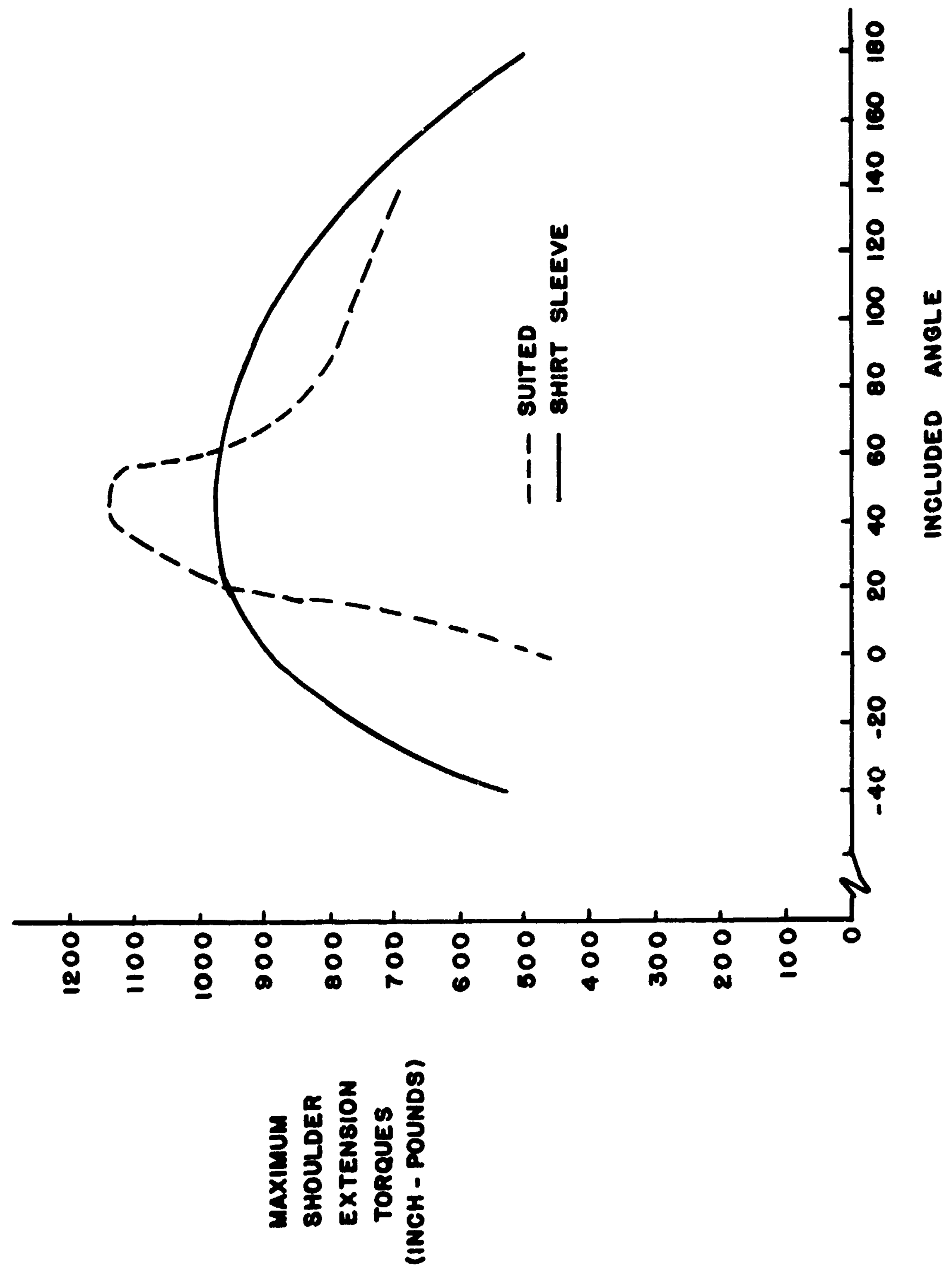
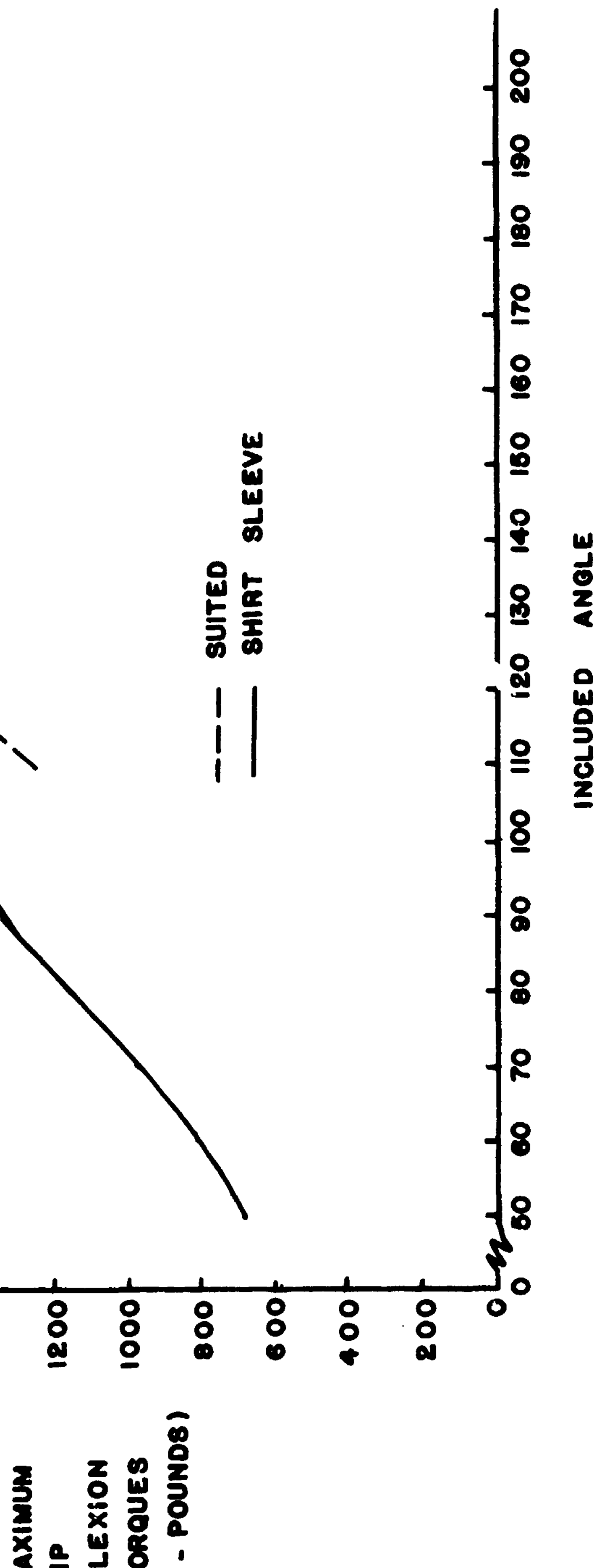
The suited values were developed from unpublished data obtained from the MSC-EVA Branch, based on tests conducted on the pressurized A7L suit.

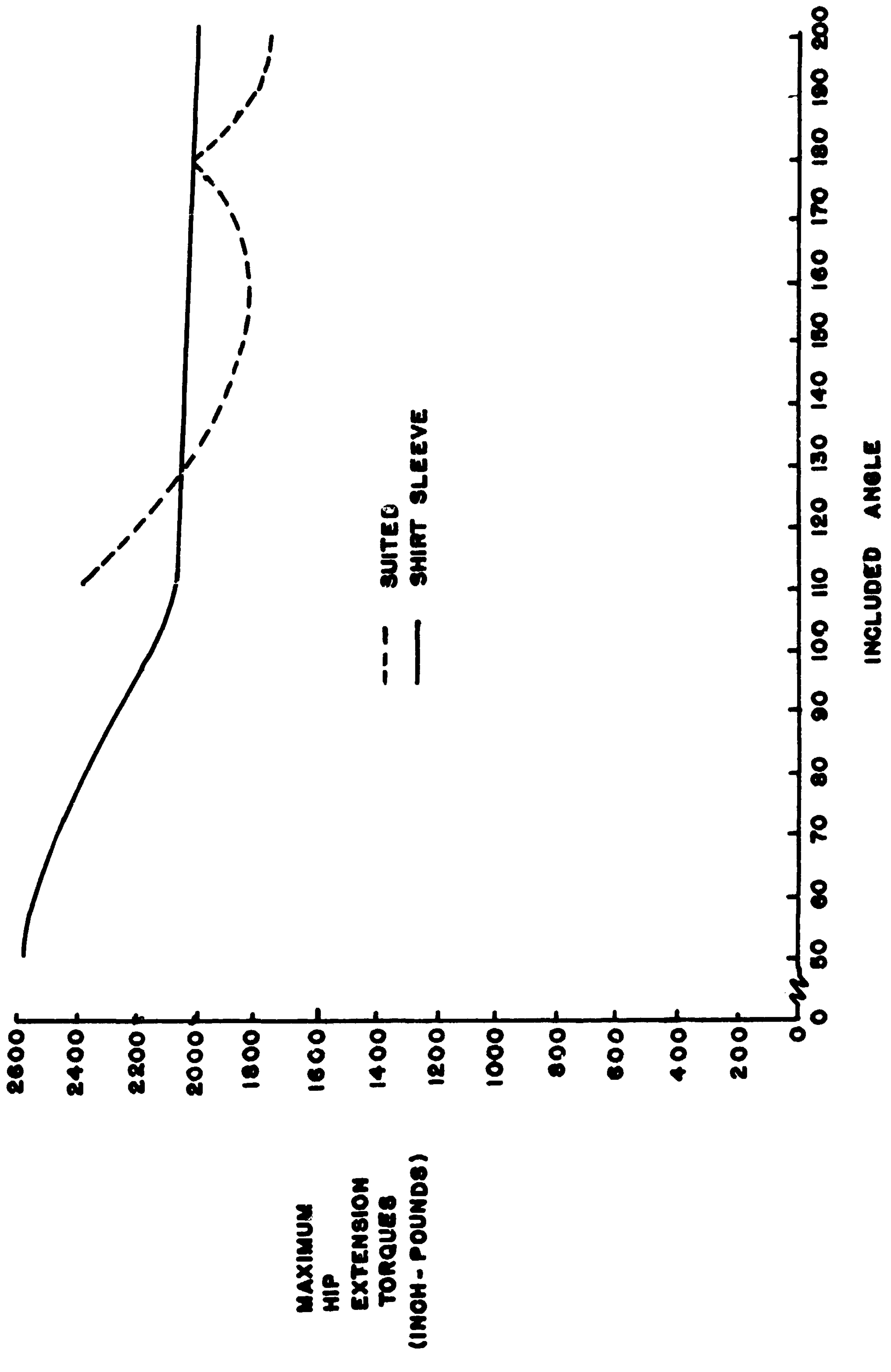

SUITED
SHIRT SLEEVE
MAXIMUM ELBOW FLEXION TORQUE (INCH - POUNDS)
800
700
600
500
400
300
200
100
0
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
INCLUDED ANGLE

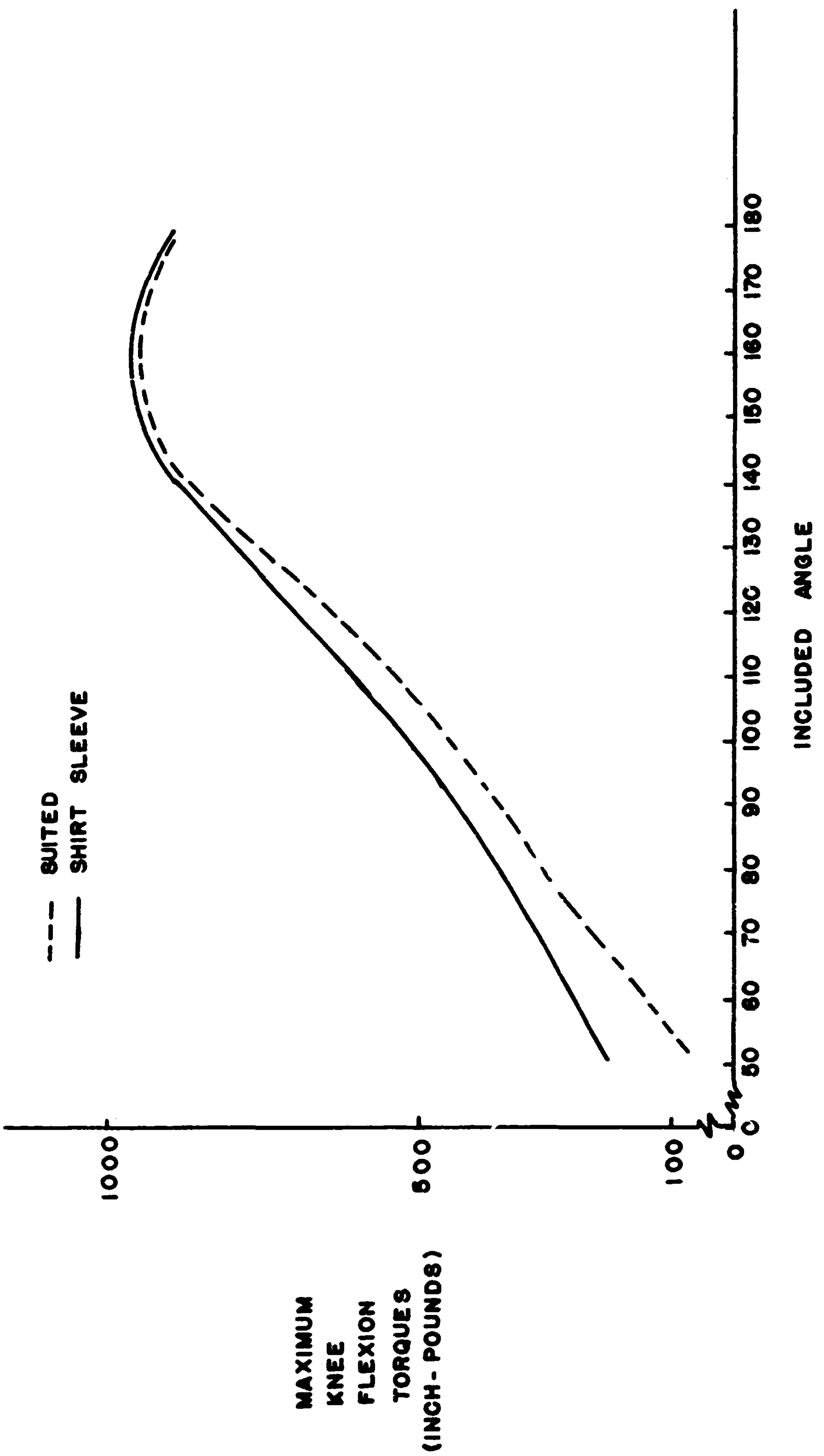

MAXIMUM ELBOW EXTENSION TORQUE (INCH-POUNDS)
600
500
400
300
200
100
0
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
INCLUDED ANGLE
SUITED
SHIRT SLEEVE

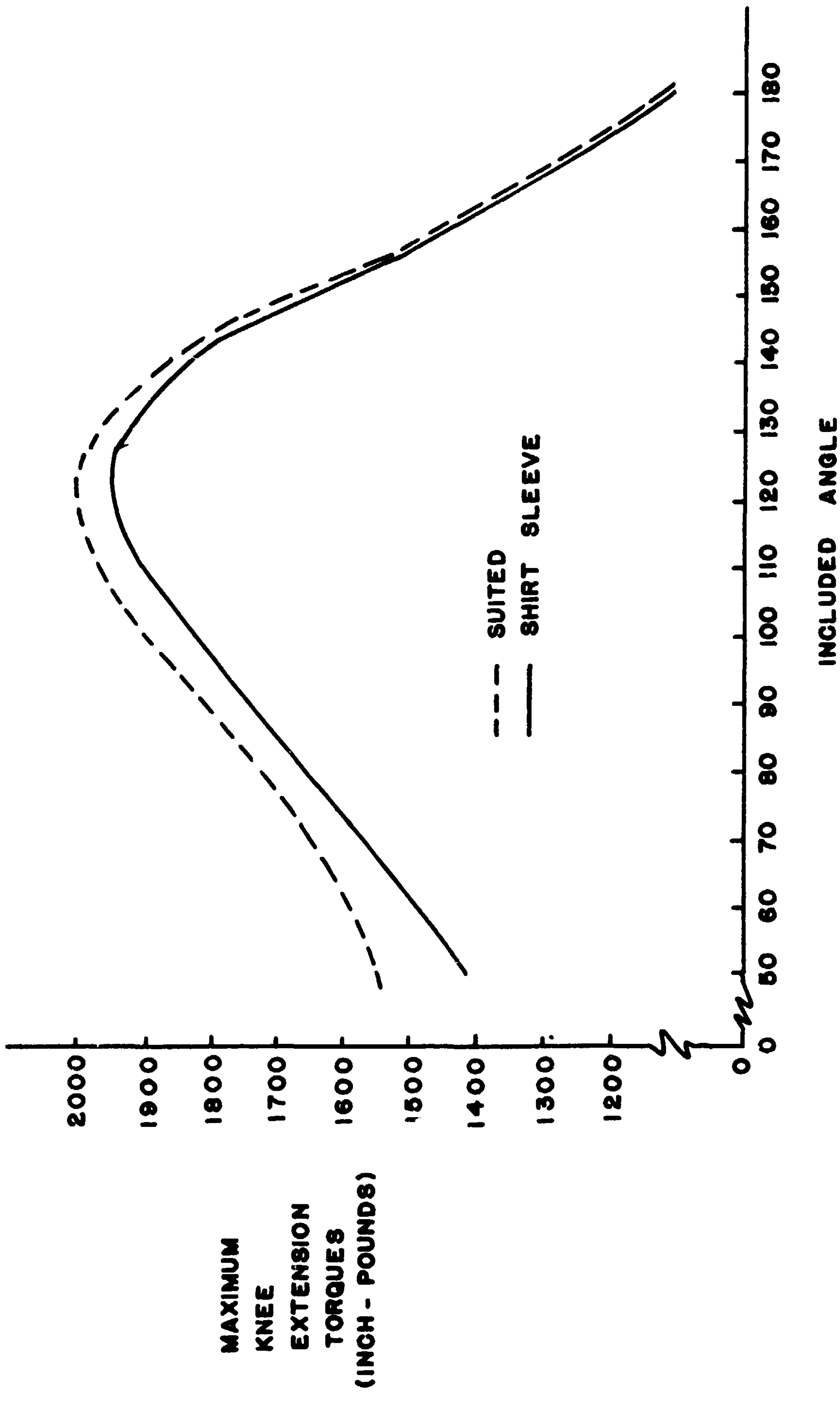

MAXIMUM
SHOULDER
FLEXION
TORQUES
(INCH - POUNDS)
1500
140C
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-40
-20
0
20
40
60
80
100
120
140
160
180
200
INCLUDED ANGLE
SUITED
SHIRT SLEEVE

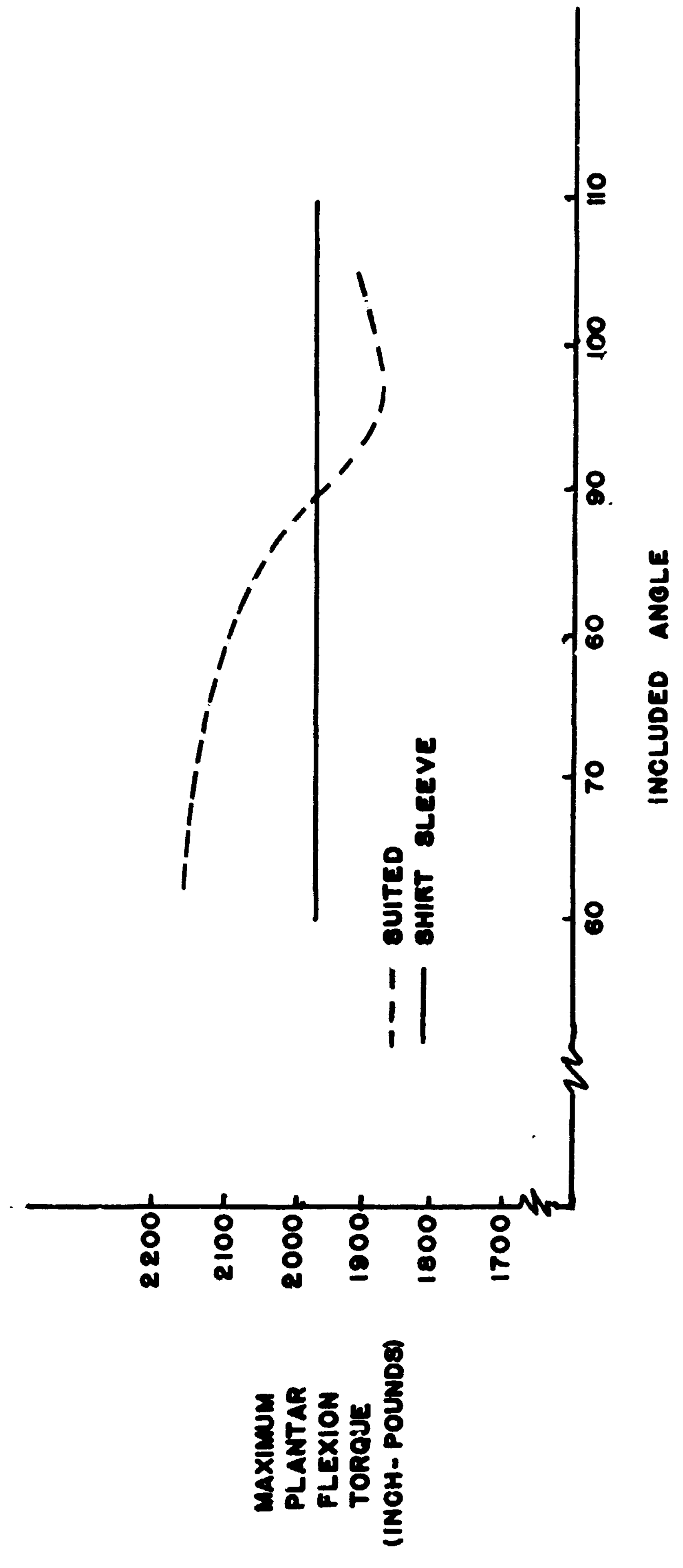

MAXIMUM
SHOULDER
EXTENSION
TORQUES
(INCH - POUNDS)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
-40
-20
0
20
40
60
80
100
120
140
160
180
INCLUDED ANGLE
SUITED
SHIRT SLEEVE


MAXIMUM HIP FLEXION TORQUES (INCH - POUNDS)
1800
1600
1400
1200
1000
800
600
400
200
0
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
INCLUDED ANGLE
SUITED
SHIRT SLEEVE


MAXIMUM
HIP
EXTENSION
TORQUES
(INCH-POUNDS)
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
INCLUDED ANGLE
SUITED
SHIRT SLEEVE


SUITED
SHIRT SLEEVE
MAXIMUM KNEE FLEXION TORQUES (INCH-POUNDS)
1000
500
100
0
INCLUDED ANGLE
0
50
60
70
80
90
100
110
120
130
140
150
160
170
180


MAXIMUM KNEE EXTENSION TORQUES (INCH - POUNDS)
2000
1900
1800
1700
1600
1500
1400
1300
1200
0
50
60
70
80
90
100
110
120
130
140
150
160
170
180
INCLUDED ANGLE
SUITED
SHIRT SLEEVE


MAXIMUM PLANTAR FLEXION TORQUE (INCH-POUNDS)
2200
2100
2000
1900
1800
1700
SUITED
SHIRT SLEEVE
60
70
60
90
100
110
INCLUDED ANGLE

APPENDIX B

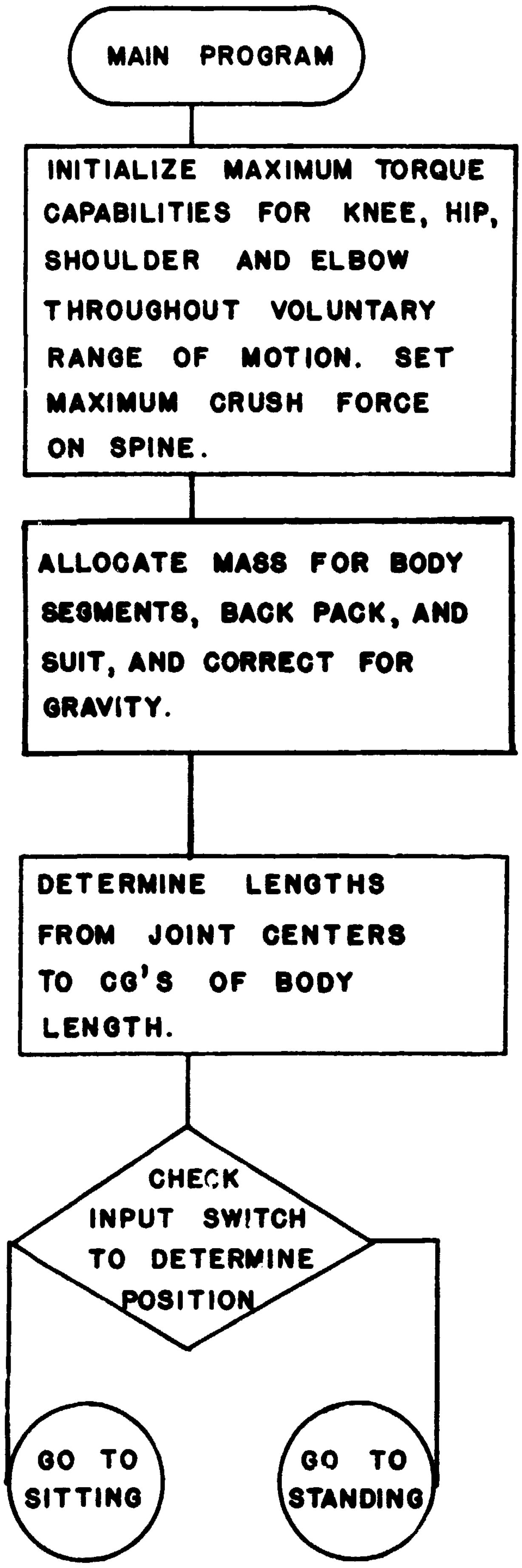
General Flow Charts of Model

The following is a general flow chart of the Biomechanical Model and of the Spine Subroutine. Other subroutines are easily understood from comments which appeaɪ in the listing of the program[1]. The program is written in Fortran IV Assembler Language, and requires 56,000 words of core to compile and excute.

[1]A program listing can be obtained from either The University of Michigan or NASA personnel directly involved in the project.

BIOMECHANICAL MODEL

FLOWCHART



VARIABLES USED IN PROGRAM

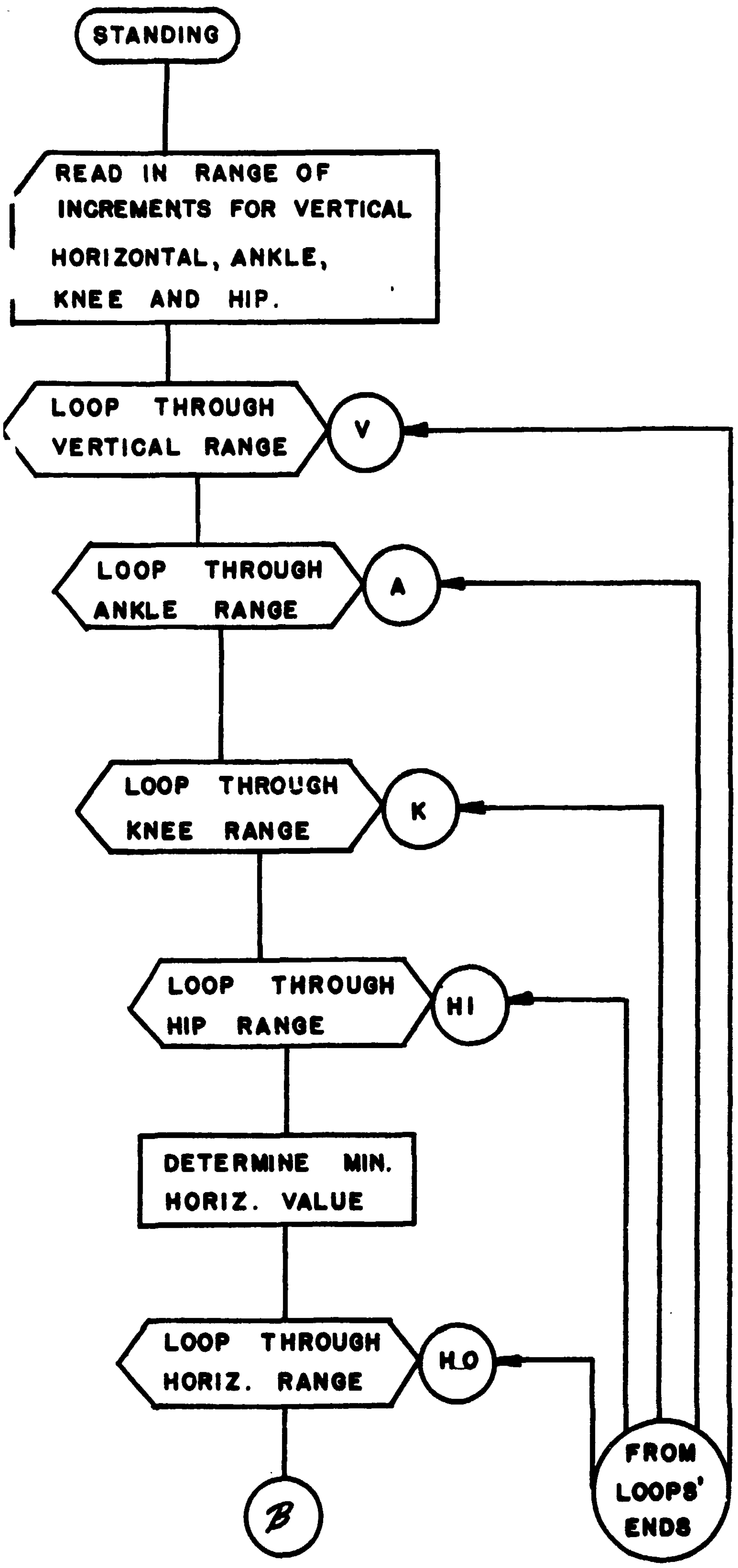
KTOR, HTOR, STORE,
STORF, ETORE, ETORF

DISC (MALE), DISC (FEMALE)

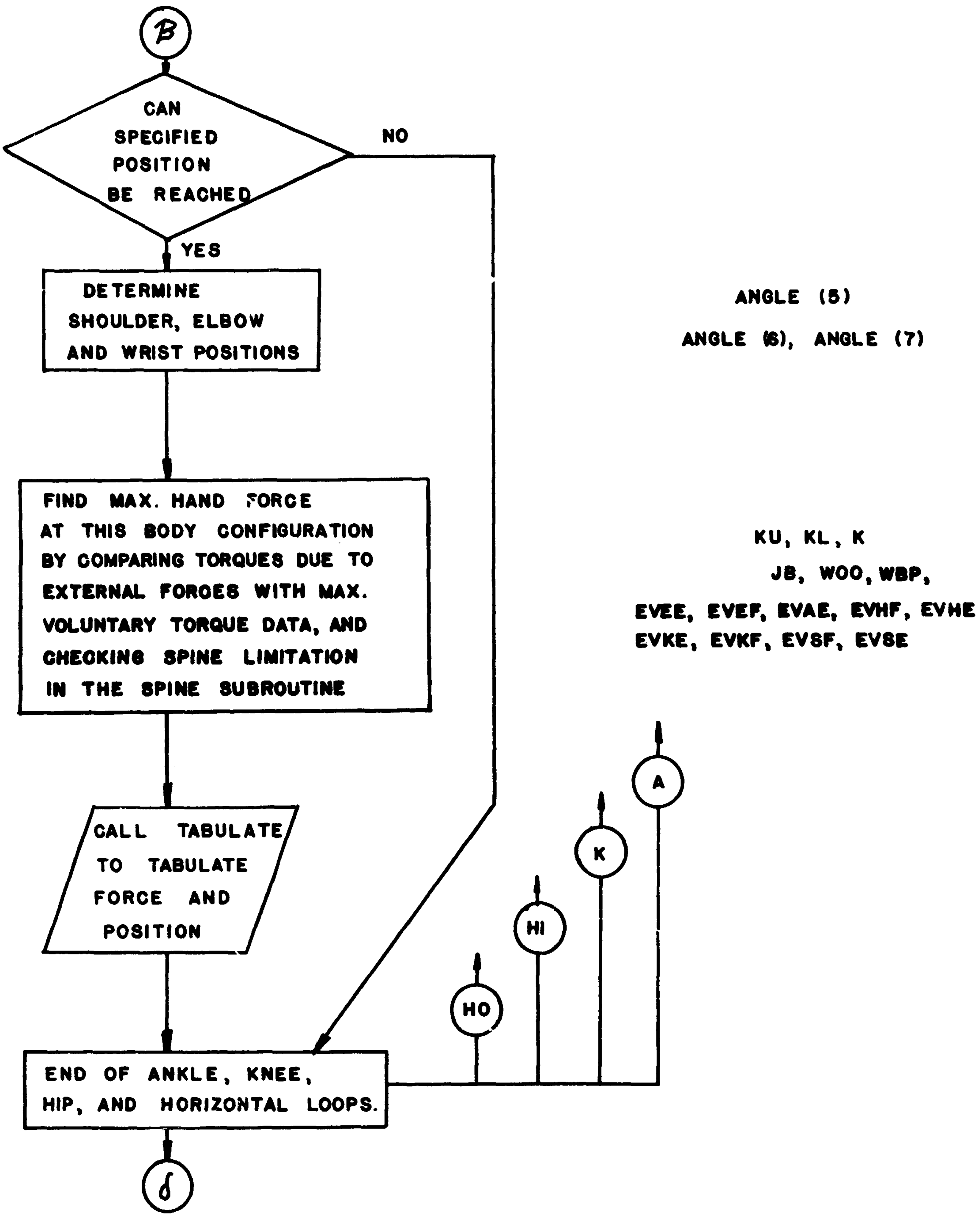
WH, WLA, WUA, WT,
WUL, WLL, WFF
GRAV, ISUIT

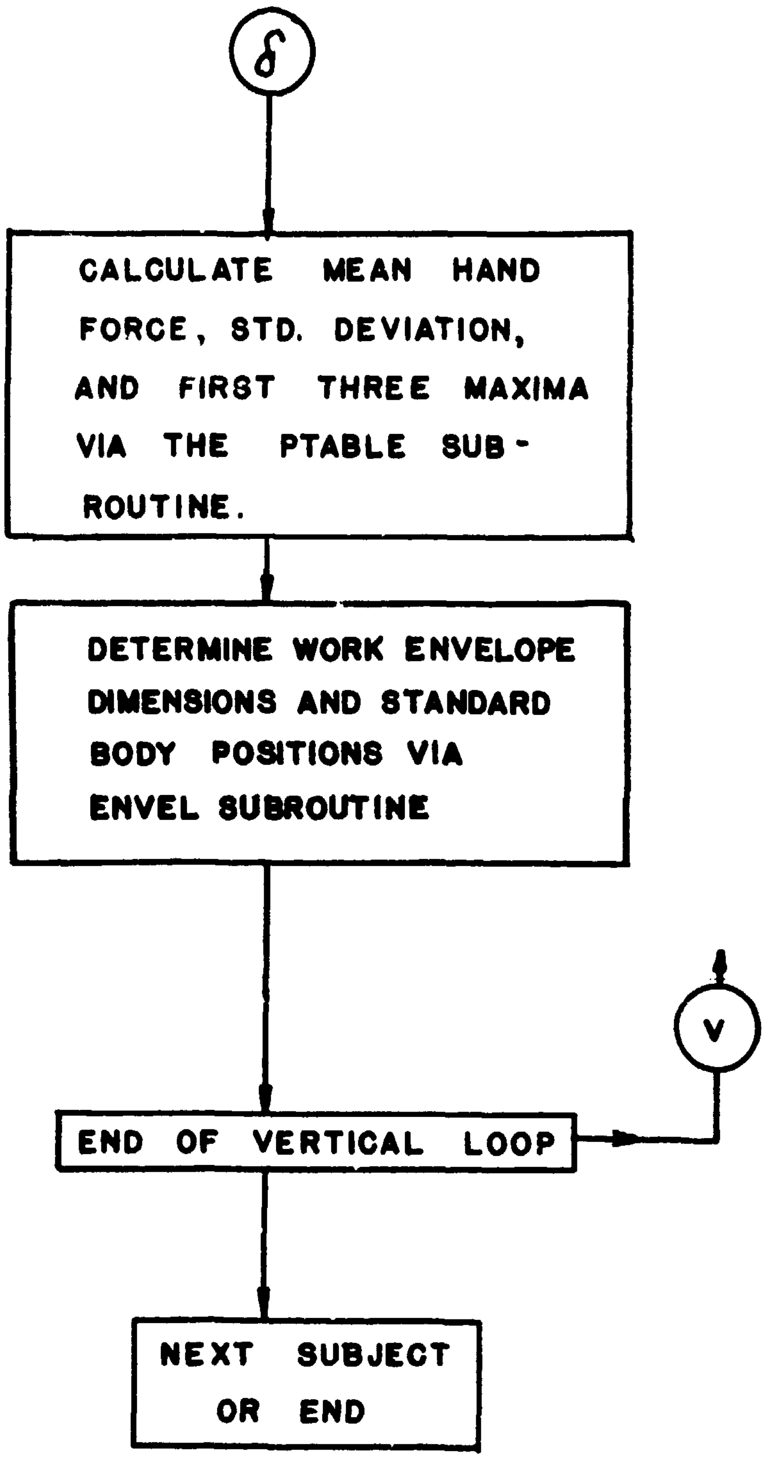
EW, ECGLA, WCGH, SE,
SCGUA, AK, ACGLL, ZKH,
ZKCGUL, FA, HTS, HS,
HCGT, HSI, SL4, ZLS

IPOS



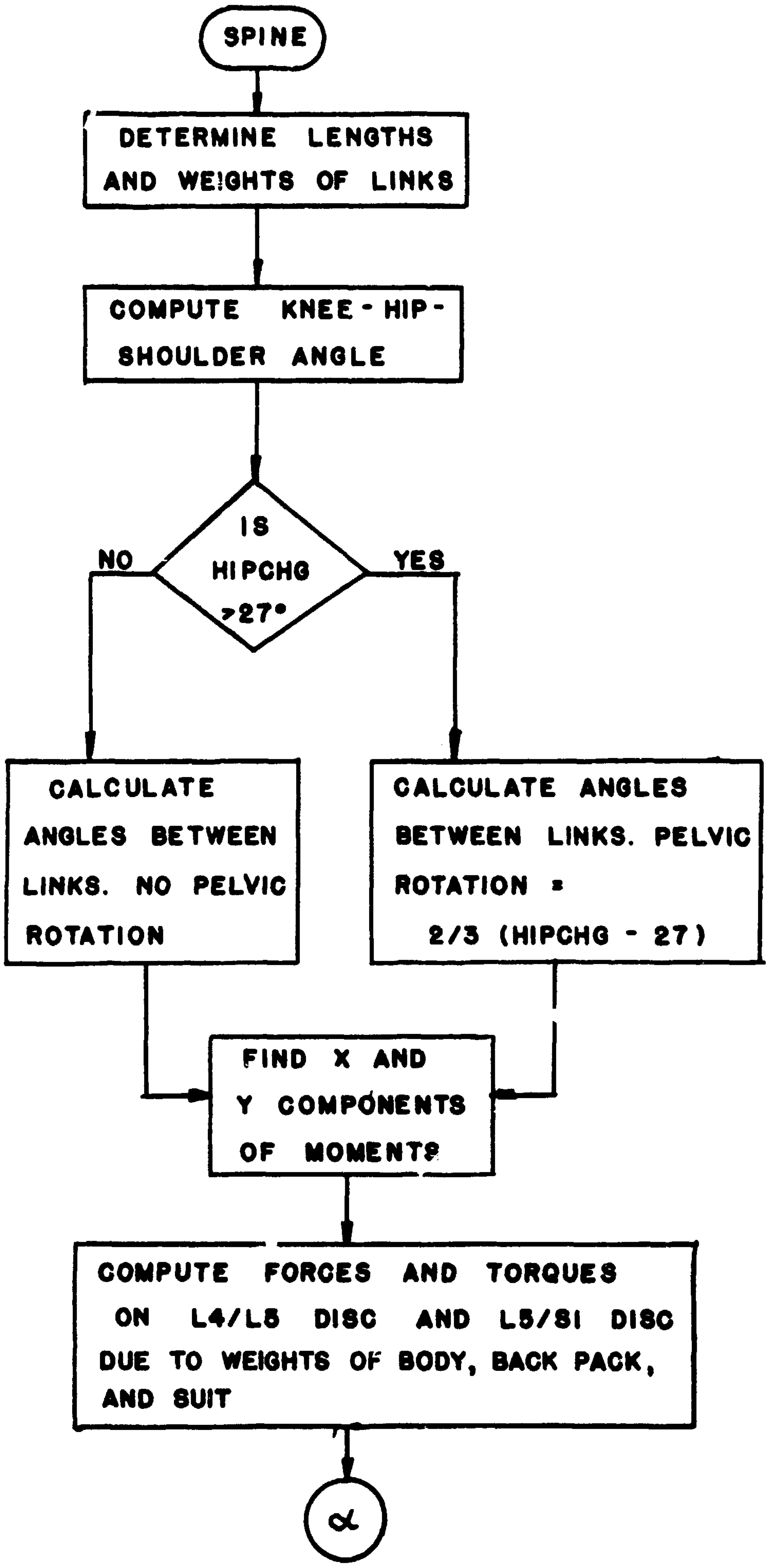
VERMIN, VERINC, VERMAX
HORMIN, HORINC, HORMAX
ANKMIN, ANKINC, ANKMAX
KNEMIN, KNEINC, KNEMAX
HIPMIN, HIPINC, HIPMAX


B
CAN SPECIFIED POSITION BE REACHED
NO
YES
DETERMINE SHOULDER, ELBOW AND WRIST POSITIONS
ANGLE (5)
ANGLE (6), ANGLE (7)
FIND MAX. HAND FORCE AT THIS BODY CONFIGURATION BY COMPARING TORQUES DUE TO EXTERNAL FORCES WITH MAX. VOLUNTARY TORQUE DATA, AND CHECKING SPINE LIMITATION IN THE SPINE SUBROUTINE
KU, KL, K
JB, WOO, WBP,
EVEE, EVEF, EVAE, EVHF, EVHE
EVKE, EVKF, EVSF, EVSE
CALL TABULATE TO TABULATE FORCE AND POSITION
A
K
HI
HO
END OF ANKLE, KNEE, HIP, AND HORIZONTAL LOOPS.
δ


δ
CALCULATE MEAN HAND FORCE, STD. DEVIATION, AND FIRST THREE MAXIMA VIA THE PTABLE SUB-ROUTINE.
DETERMINE WORK ENVELOPE DIMENSIONS AND STANDARD BODY POSITIONS VIA ENVEL SUBROUTINE
V
END OF VERTICAL LOOP
NEXT SUBJECT OR END

SPINE SUBROUTINE

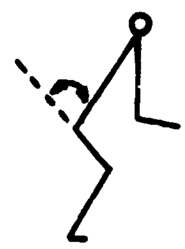
FLOWCHART



VARIABLES USED IN PROGRAM

RX, RY

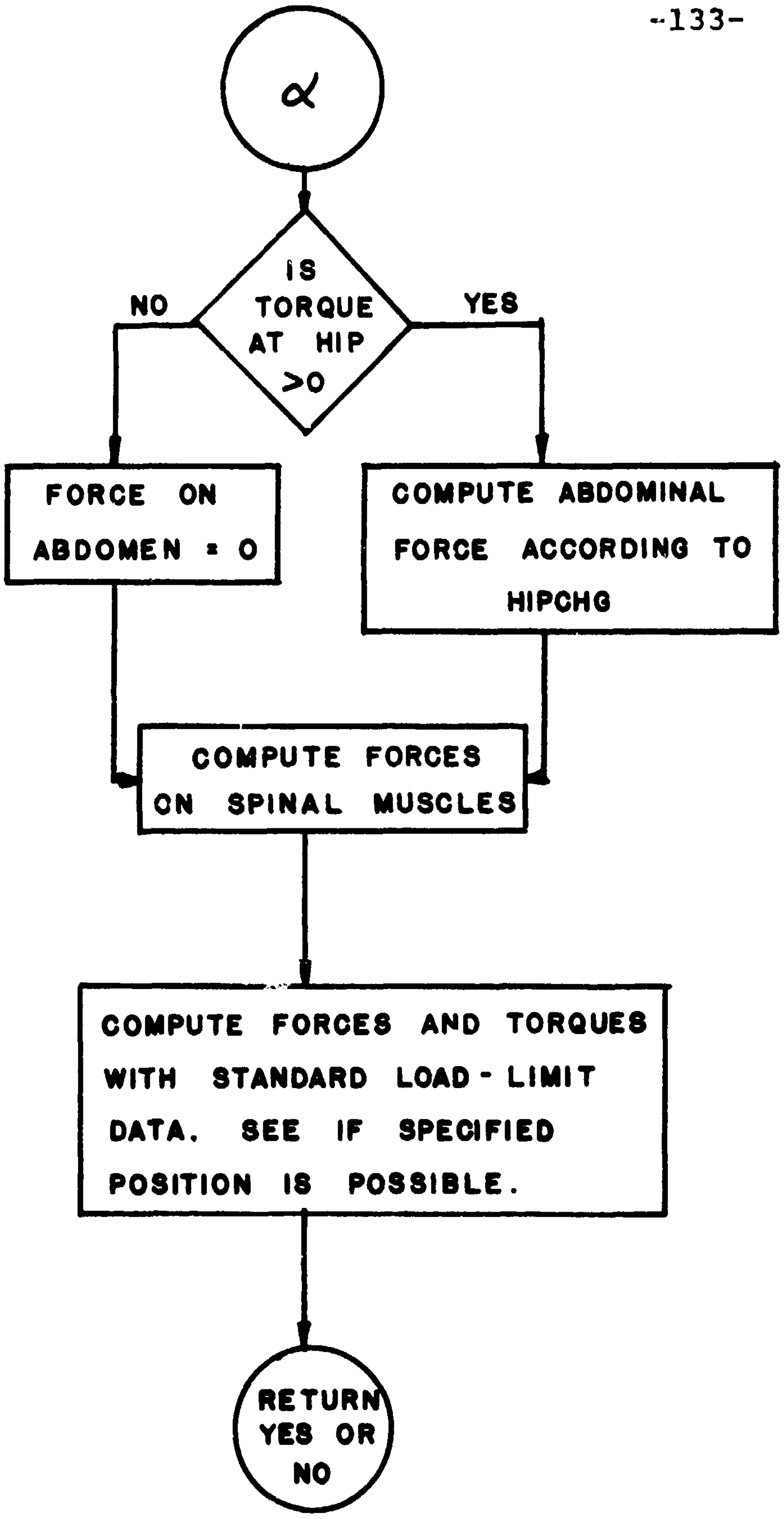
HIPCHG



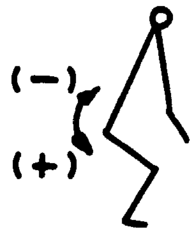
ANGPEL

RNX, RNY

RTX, RTY, TL5
TL5BP1, TL5BP2



VARIABLES



TH = REACTIVE TORQUE AT HIPS

ABDOM

ZMUSL

LIMIT

APPENDIX C

WORK ENVELOPE DIMENSIONS, STANDARD BODY POSITIONS, AND PREDICTED HAND FORCES FOR SPECIFIC HAND HEIGHTS

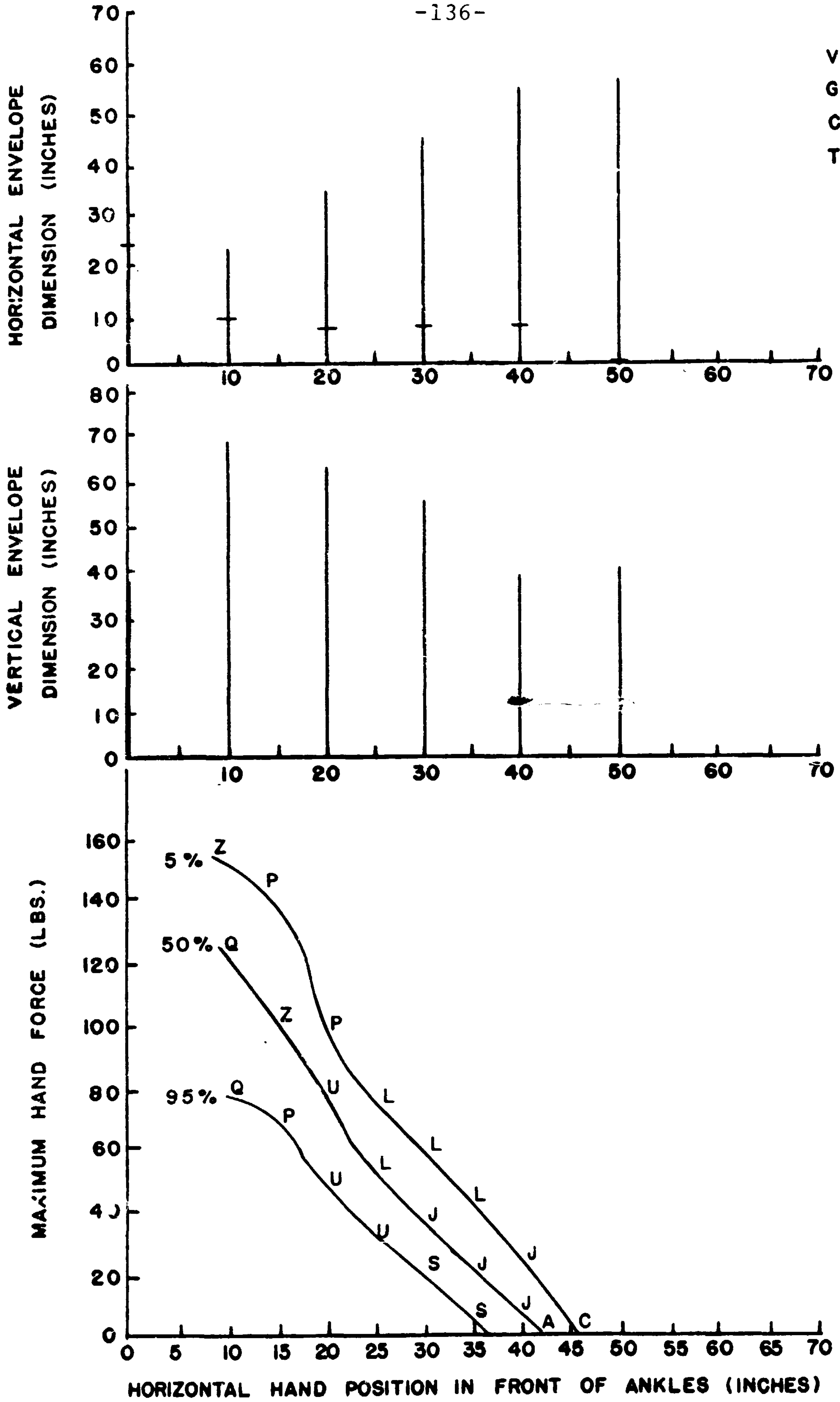
This appendix contains graphs which depict predicted two-handed force capabilities for the specific hand heights noted on the "equal hand force graphs" contained in Sections III and IV. The graphs in this appendix are keyed to the equal hand force graphs by the number beginning with a "C" in the upper right hand corner, which corresponds to the numbers along the right hand border of the equal hand force graphs.

Additional design information is available in the graphs in this Appendix in the form of both predicted rectangular work envelopes necessary to encompass 95% of the male population, and illustrations of the body configurations necessary to produce the hand force predictions. The work envelope dimensions are presented as bar graphs. The upper bar graphs represent the horizontal work envelope dimensions, (the cross hatch depicts the ankle horizontal displacement, with the lower portion of the line predicting the most posterior projection beyond the ankle, and the upper portion of the line depicting the most anterior projection of the body beyond the ankles). The lower bar graph predicts the vertical work envelope dimension necessary to allow a man as large or larger than 95% of the male population to assume a position where-in he can produce the two-handed forces predicted in the lower line graph.

The bottom graph depicts the two-handed force predictions for the conditions depicted in the upper right hand corner. The letters on the graphs refer to "standardized" body configurations assumed by a person when exerting a maximum, standing, two-handed force. A set of these "standardized" body configurations is attached to the end of this appendix. These body configurations are approximate illustrations of the actual body configurations produced by the simulations (an average of $\pm 20°$ from each articulation was used). To estimate the specific body configurations which would allow a person to exert a maximum, standing, two-handed force for a specific physical activity, it is recommended that the biomechanical model be used to simulate the specific activity. This is necessary, since the body configurations are mutually dependent on all of the variables described in Section II of this report, and hence an extremely complex and an extensive amount of data is generated from a general hand force evolution, such as performed for this report. It might also be noted that the conditions which limit an average man when lifiting, pushing, or pulling with both hands (1.0 g. and shirt-sleeved), in the standard body configurations are outputted with each computer run.

C-1

VERT: 30"
GRAV: 1.0 G
CLOTH: SHIRTSLEEVED
TASK: LIFTING



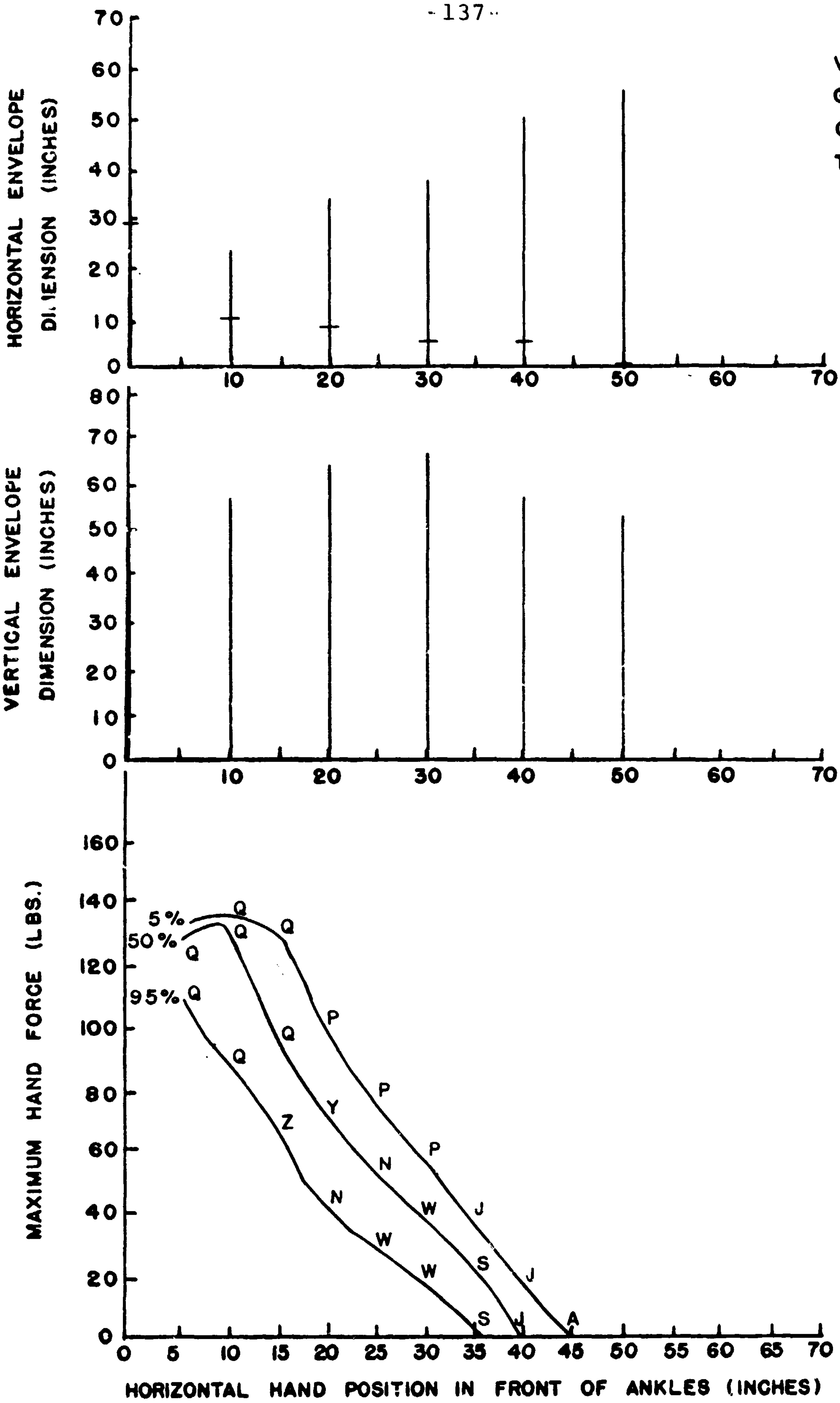
C-2

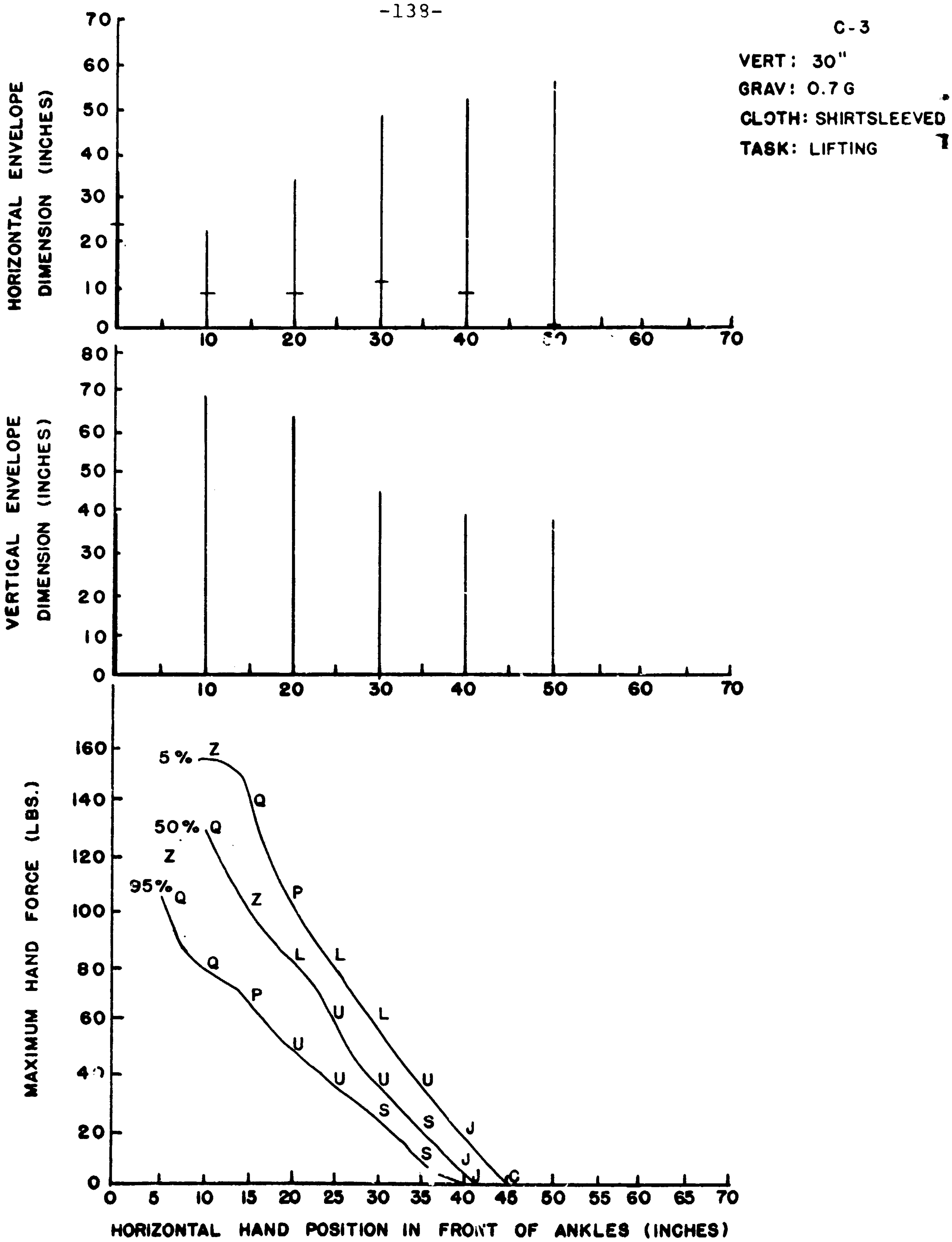
VERT: 50"

GRAV: 1.0 G

CLOTH: SHIRTSLEEVED

TASK: LIFTING




C-3
VERT: 30"
GRAV: 0.7 G
CLOTH: SHIRTSLEEVED
TASK: LIFTING
HORIZONTAL ENVELOPE DIMENSION (INCHES)
VERTICAL ENVELOPE DIMENSION (INCHES)
MAXIMUM HAND FORCE (LBS.)
5 %
50 %
95 %
HORIZONTAL HAND POSITION IN FRONT OF ANKLES (INCHES)

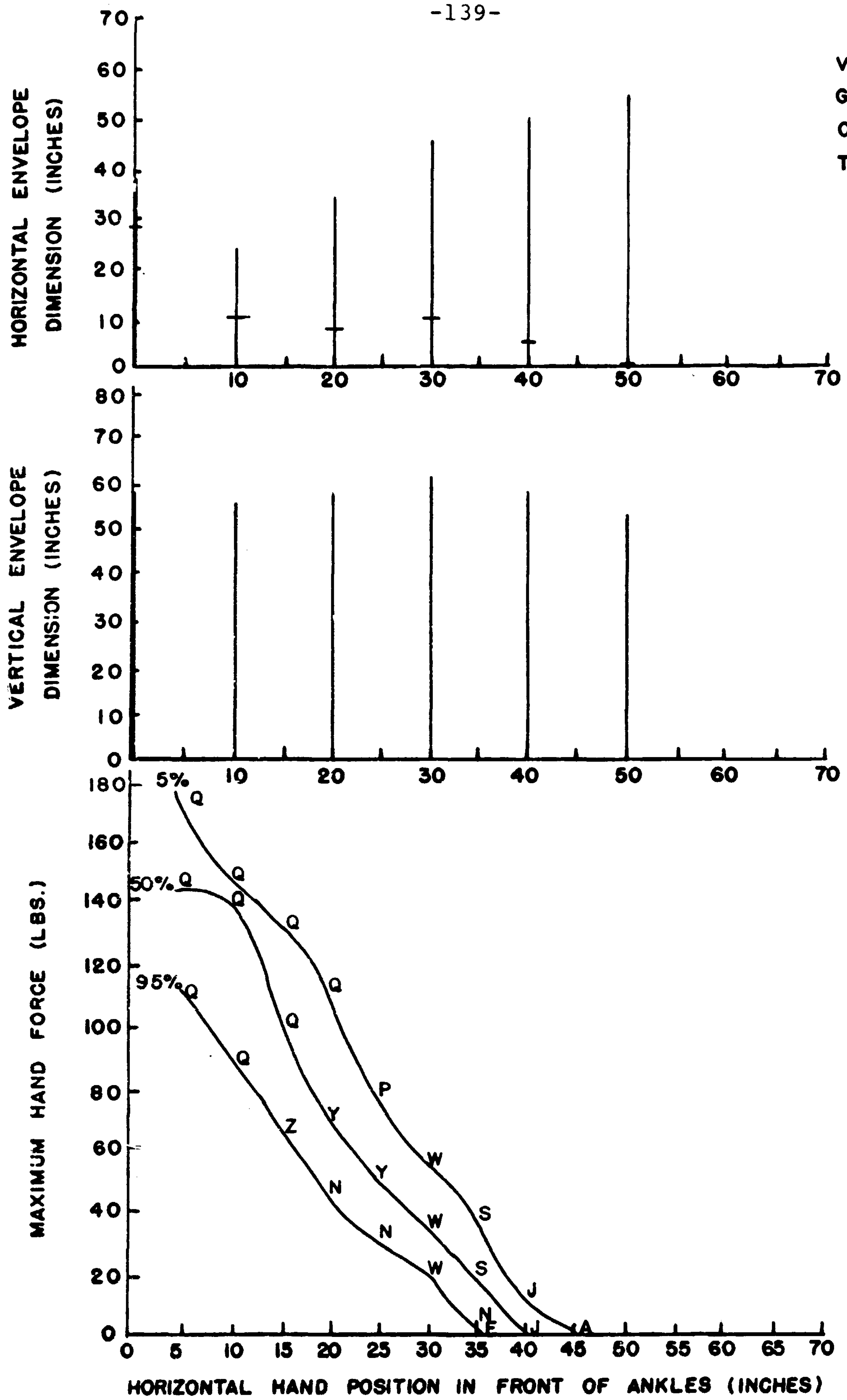
C- 4

VERT: 50"

GRAV: 0.7G

CLOTH: SHIRTSLEEVED

TASK: LIFTING



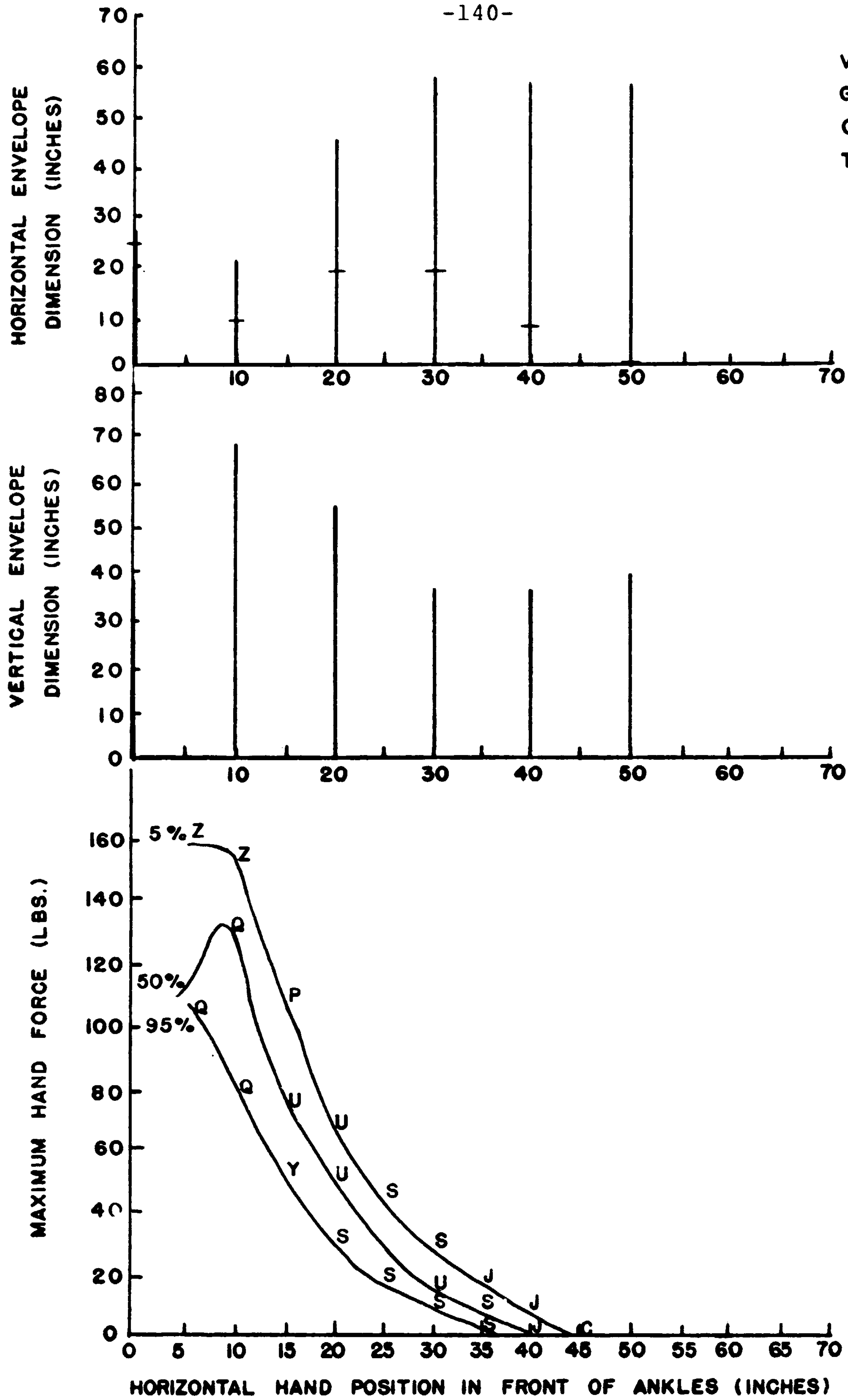
C-5

VERT: 30"

GRAV: 0.2G

CLOTH: SHIRTSLEEVED

TASK: LIFTING



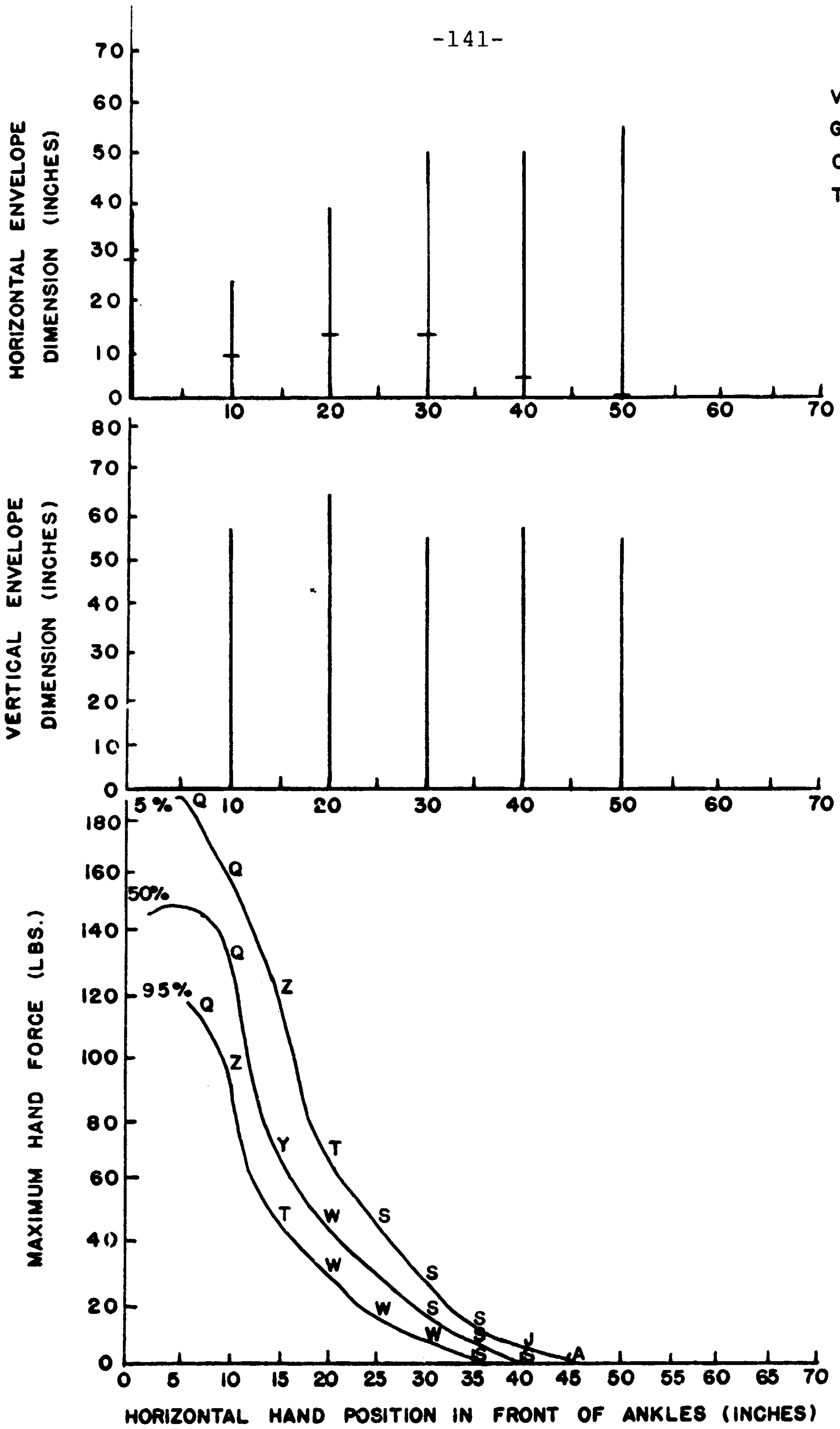
C-6

VERT: 50"

GRAV: 0.2 G

CLOTH: SHIRTSLEEVED

TASK: LIFTING



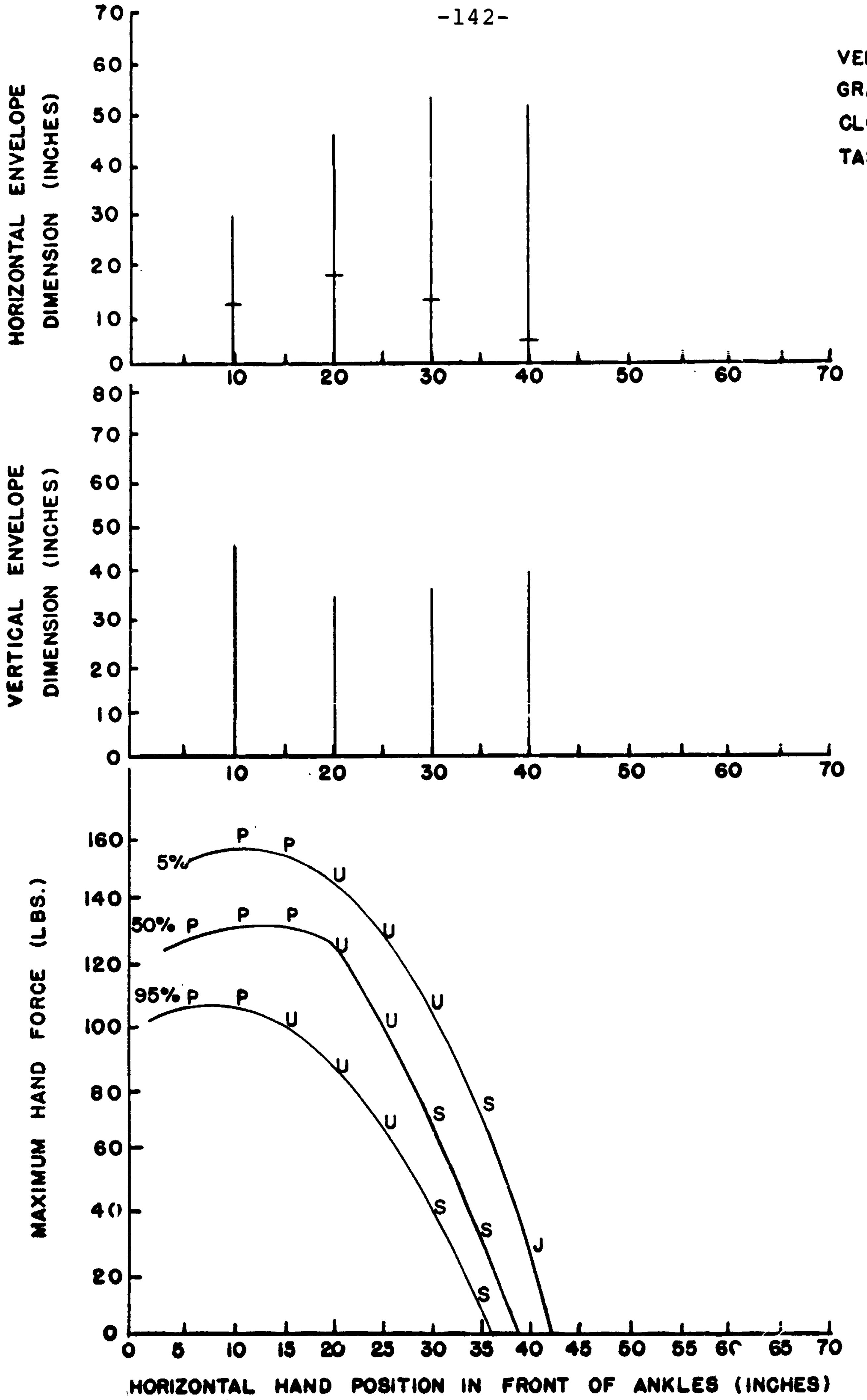
C-7

VERT: 20"

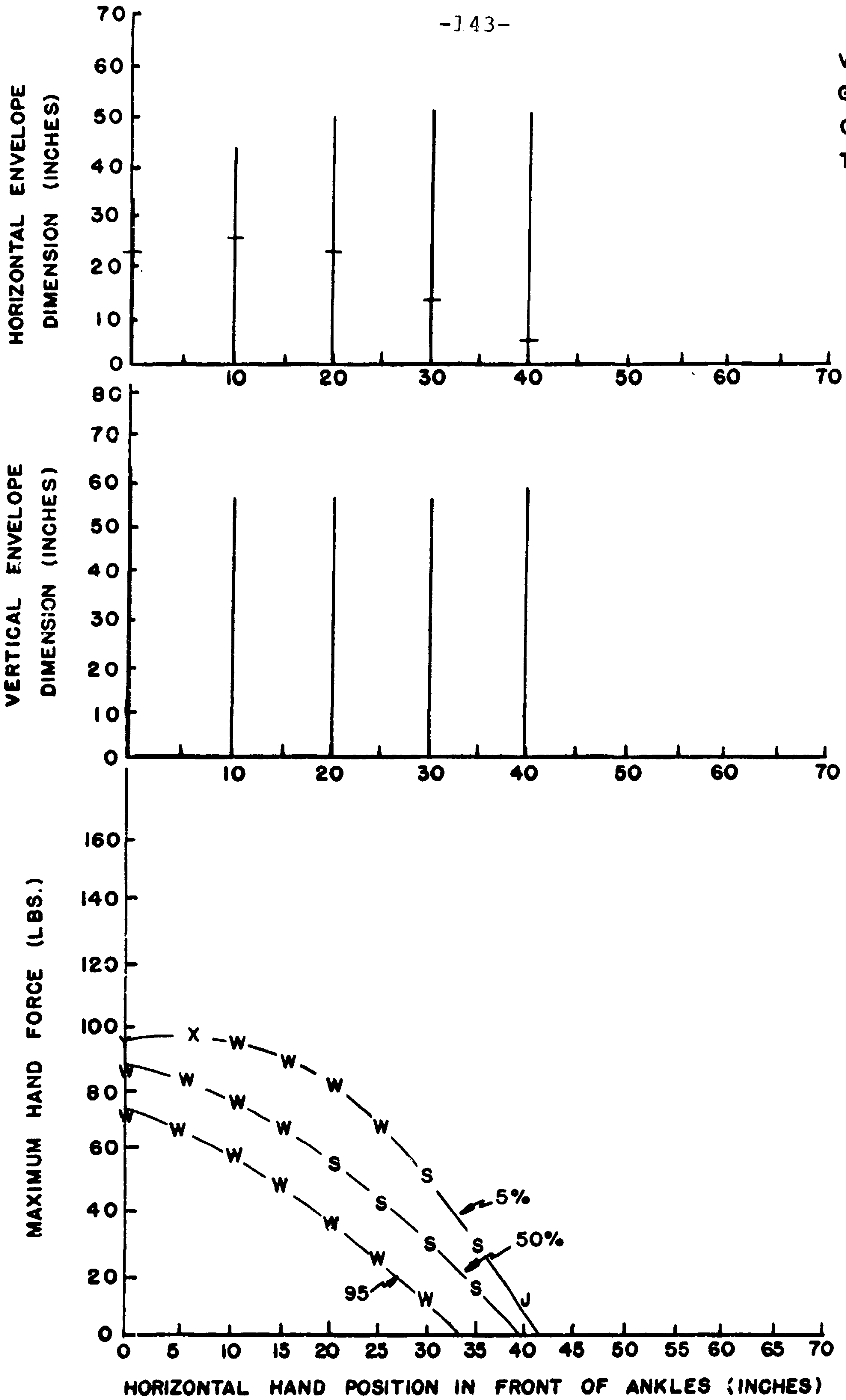
GRAV: 1.0 G

CLOTH: SHIRTSLEEVED

TASK: PULLING

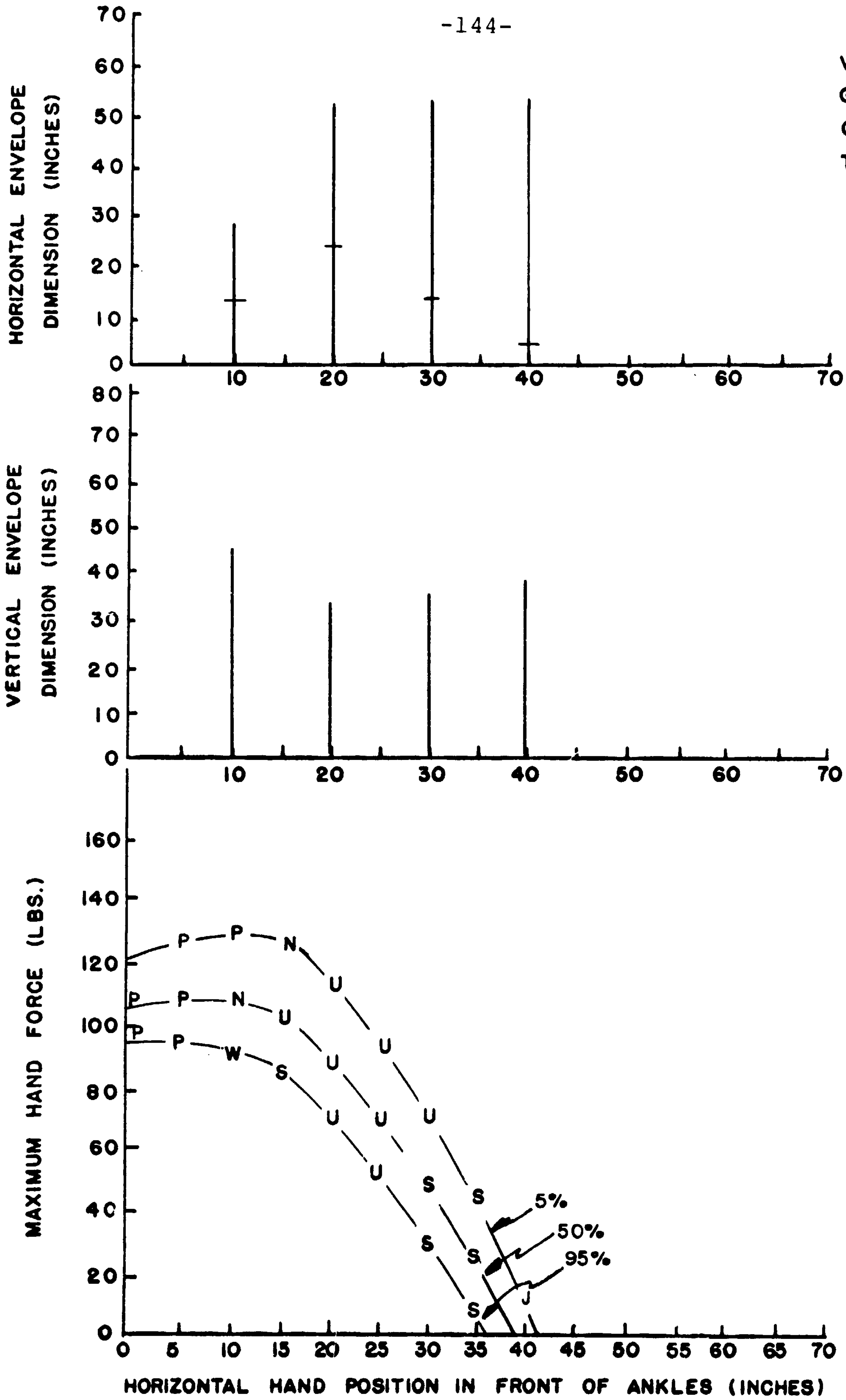


C- 8
VERT: 50"
GRAV: 1.0 G
CLOTH: SHIRTSLEEVED
TASK: PULLING

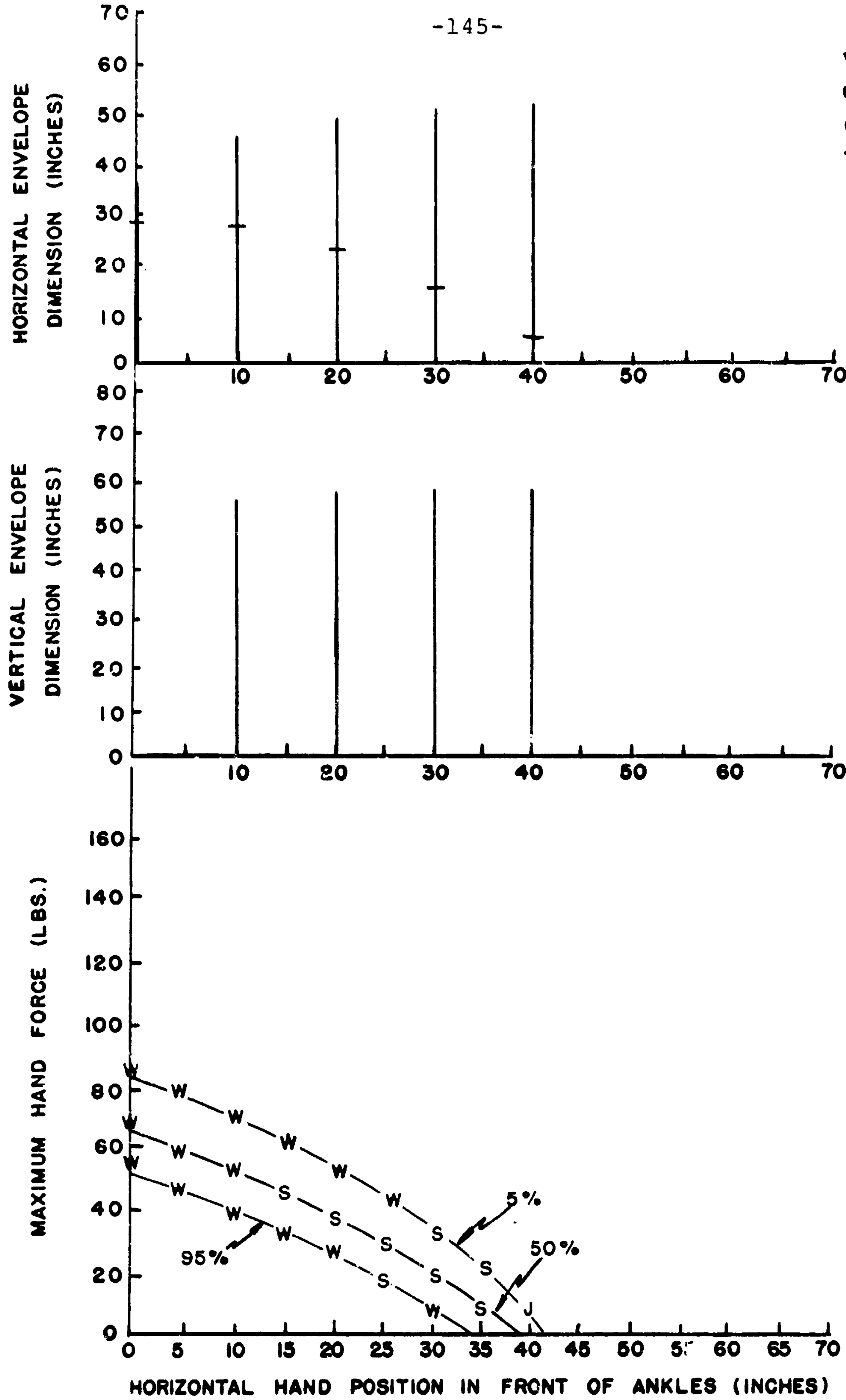


C-9

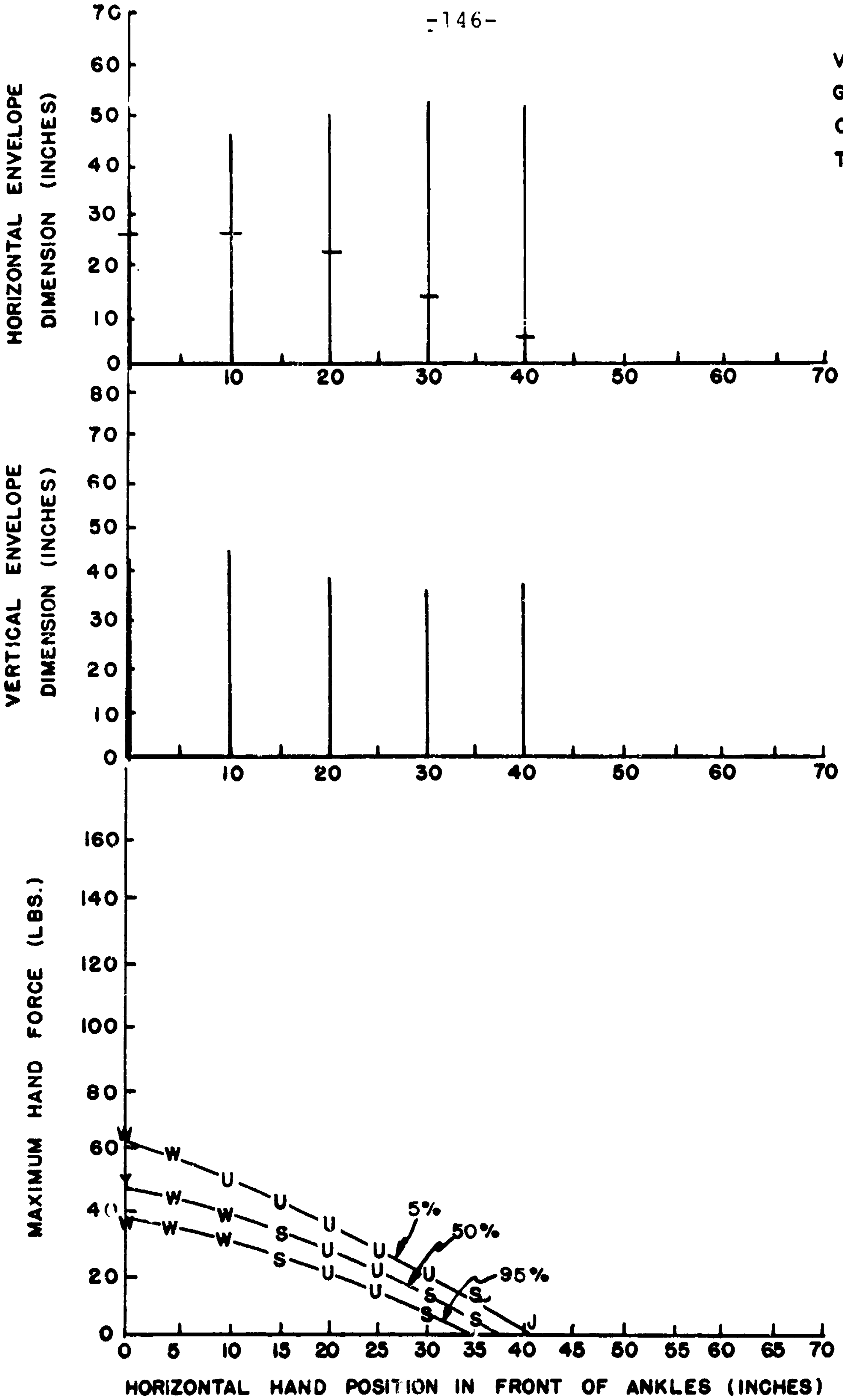
VERT: 20"
GRAV: 0.7G
CLOTH: SHIRTSLEEVED
TASK: PULLING



VERT: 50"
GRAV: 0.7G
CLOTH: SHIRTSLEEVED
TASK: PULLING

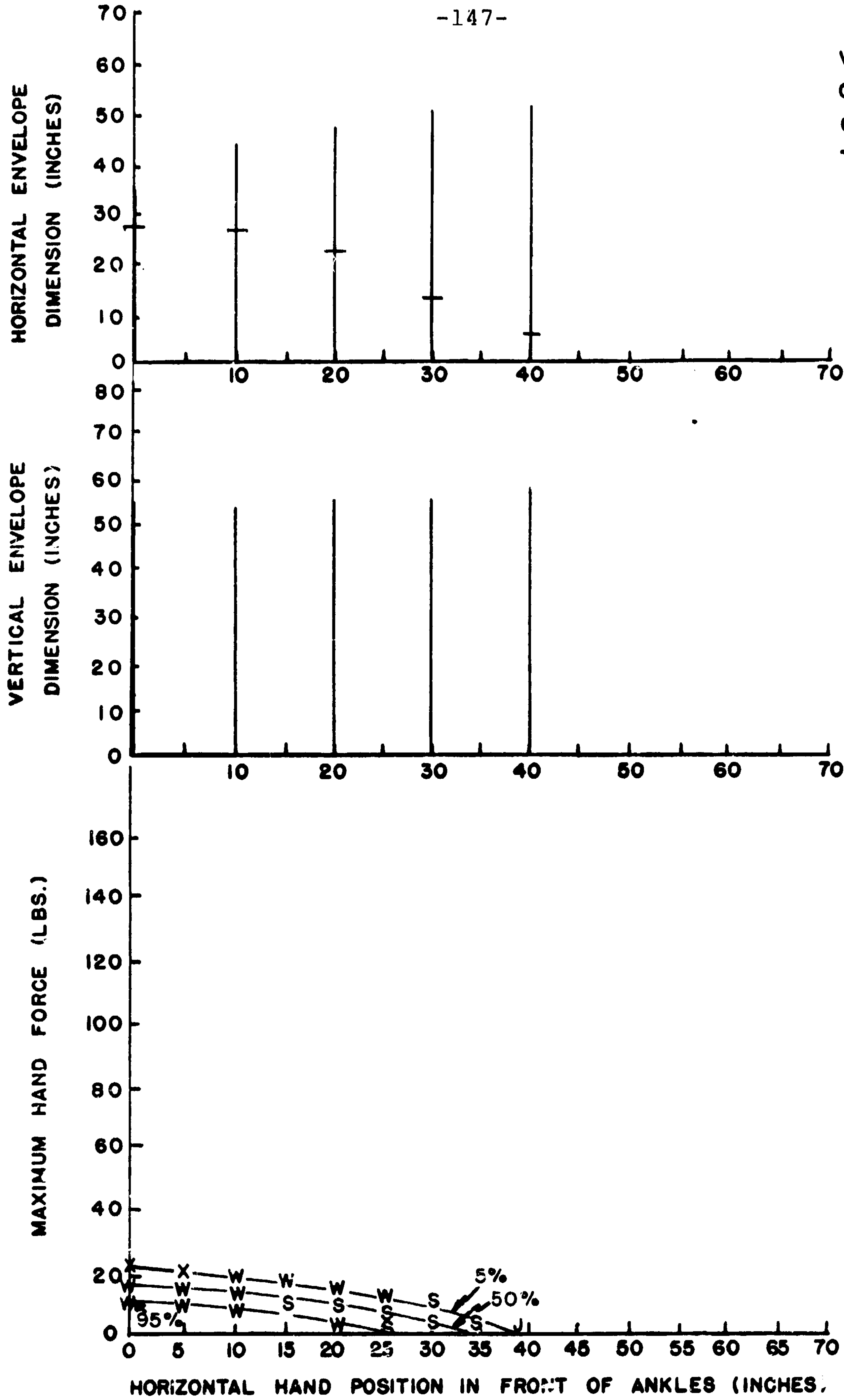


C-11
VERT: 20"
GRAV: 0.2G
CLOTH: SHIRTSLEEVED
TASK: PULLING



C-12

VERT: 50"
GRAV: 0.2 G
CLOTH: SHIRTSLEEVED
TASK: PULLING



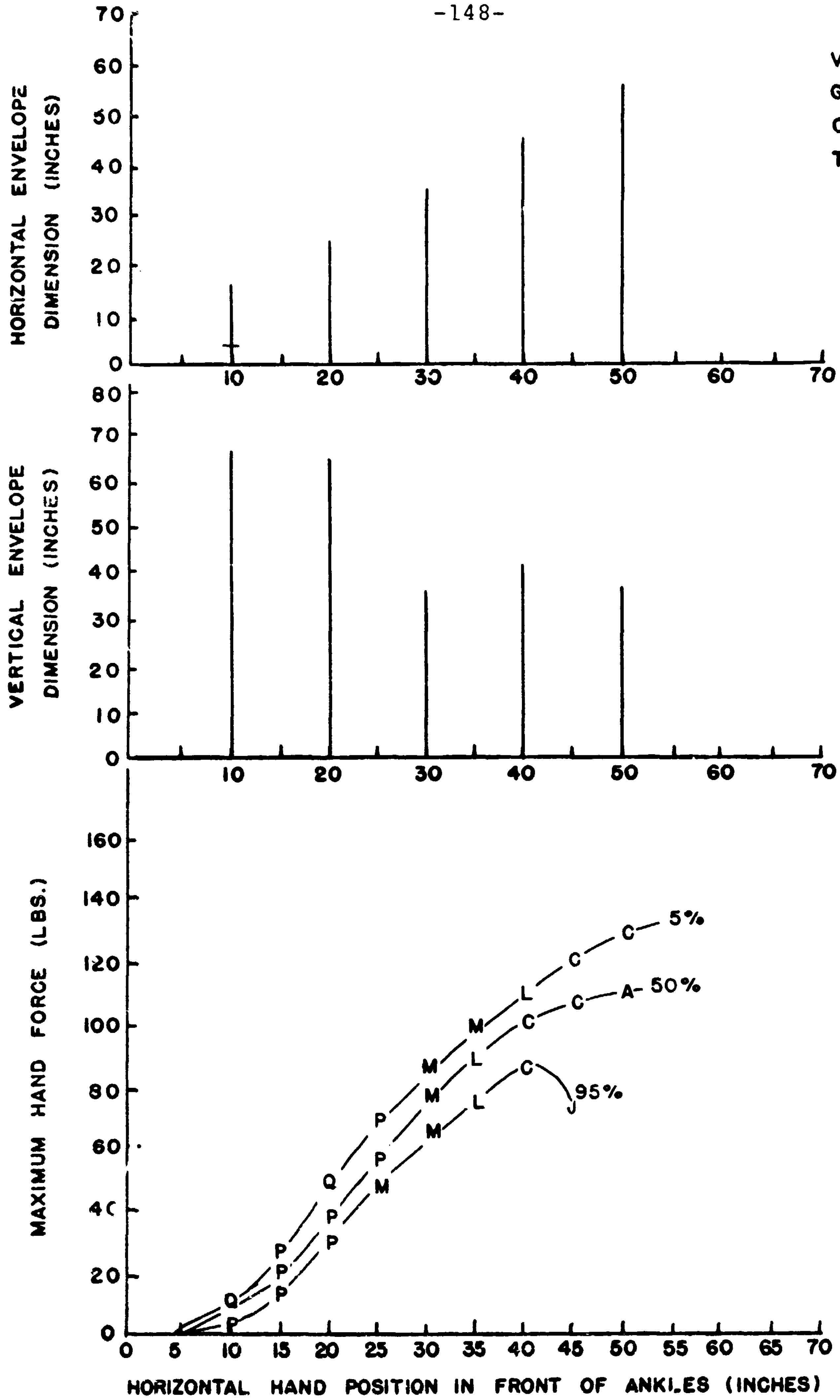
C-13

VERT: 30"

GRAV: 1.0 G

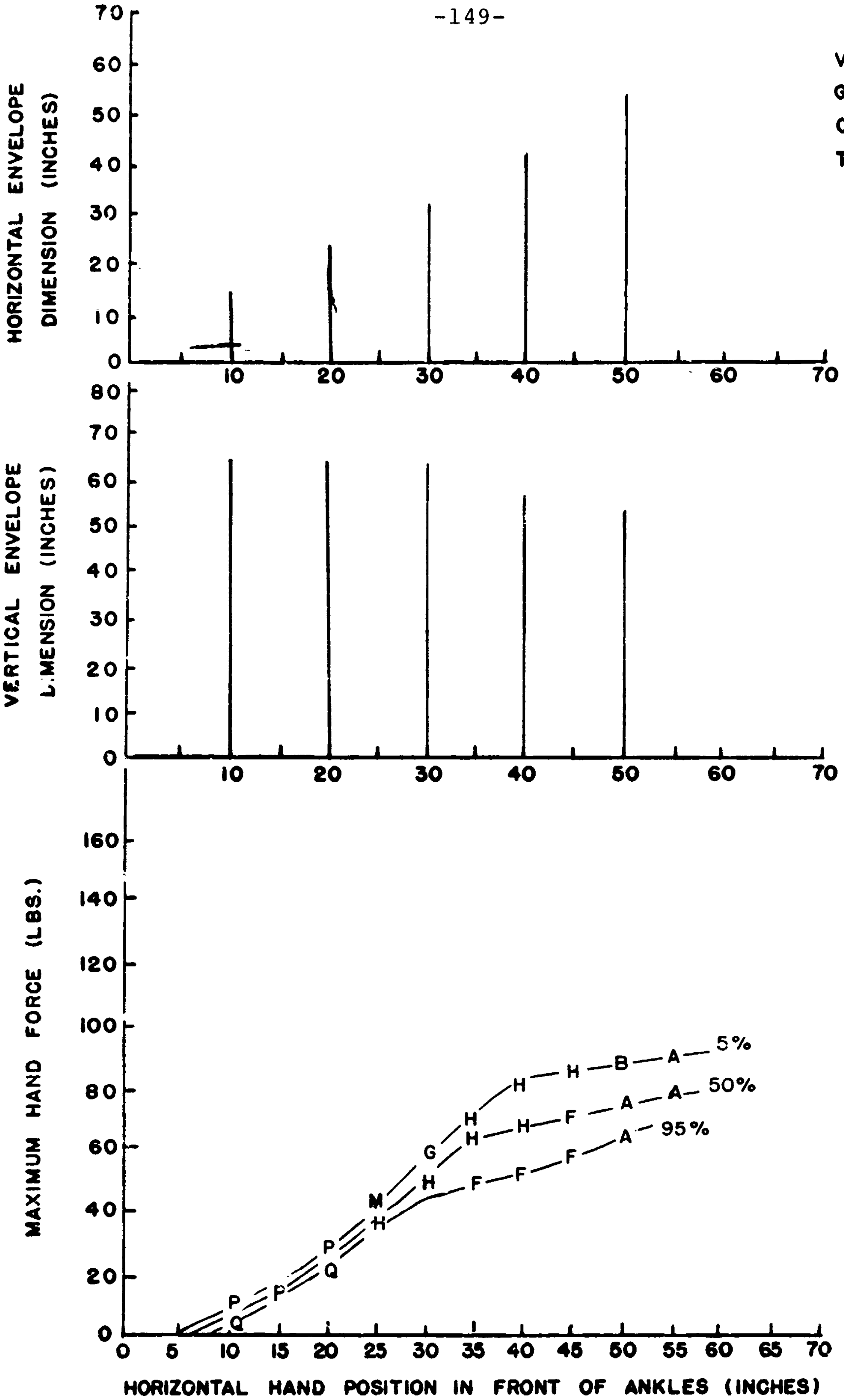
CLOTH: SHIRTSLEEVED

TASK: PUSHING



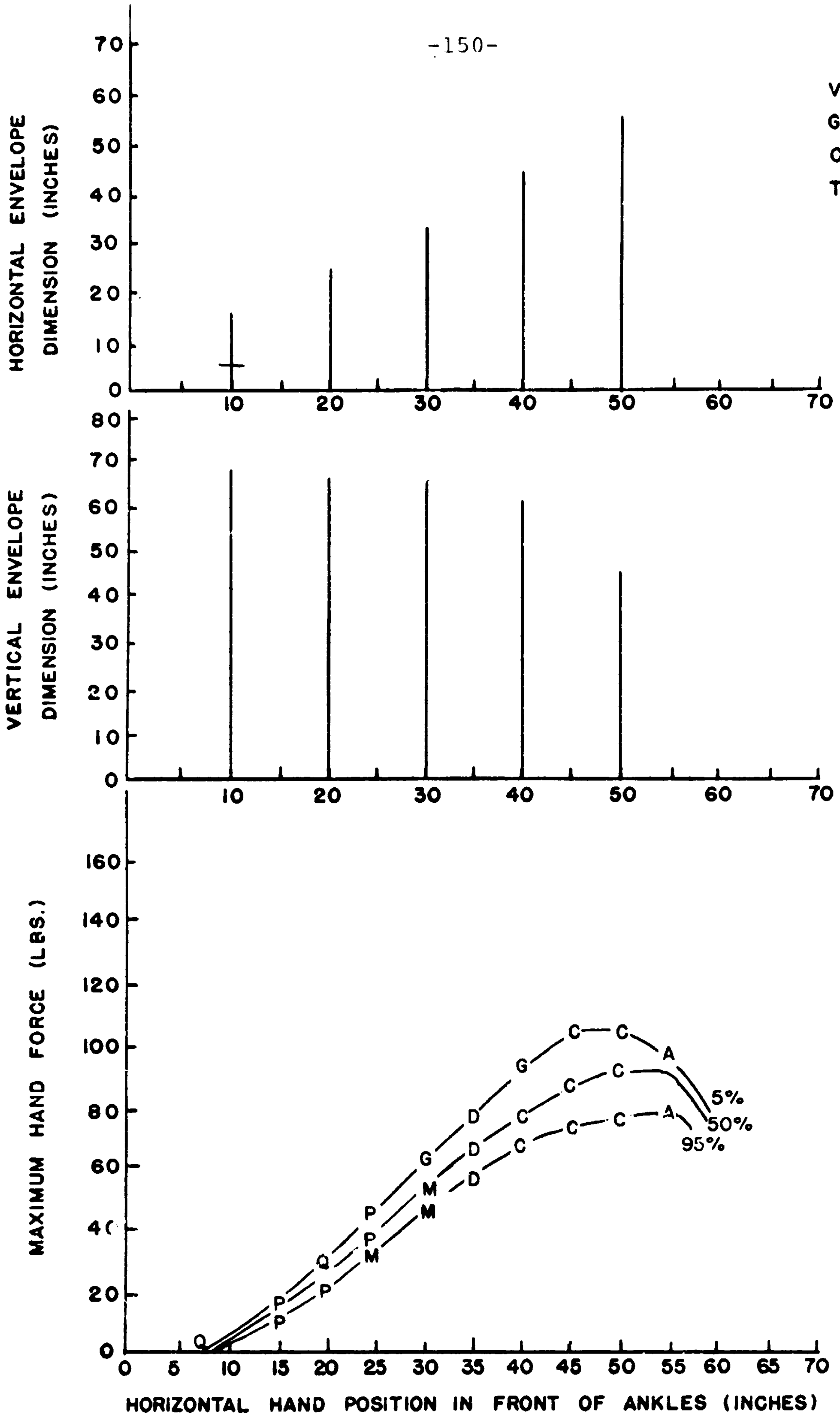
C-14

VERT: 50"
GRAV: 1.0 G
CLOTH: SHIRTSLEEVED
TASK: PUSHING



C-15

VERT: 30"
GRAV: 0.7G
CLOTH: SHIRTSLEEVED
TASK: PUSHING



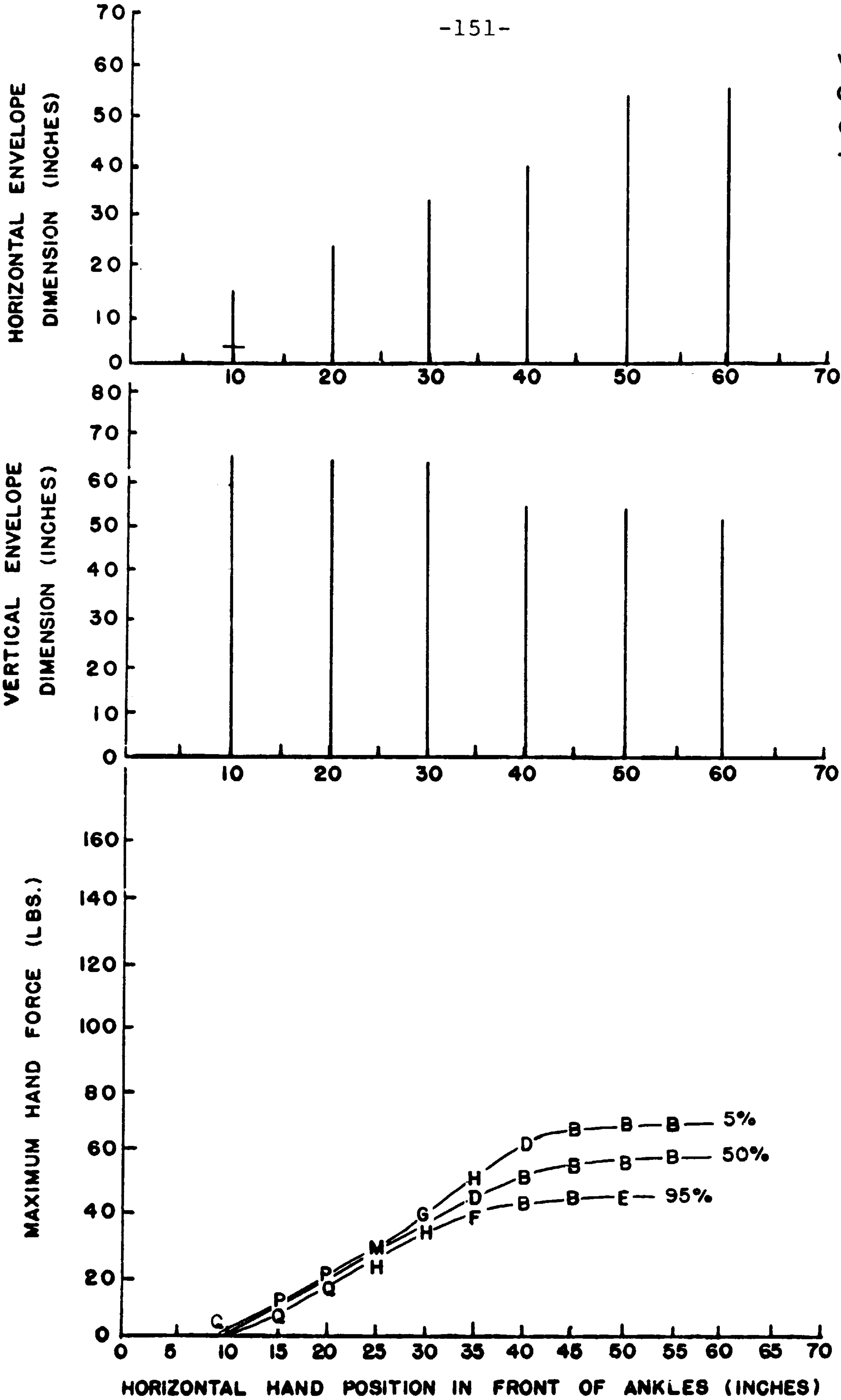
C-16

VERT: 50"

GRAV: 0.7 G

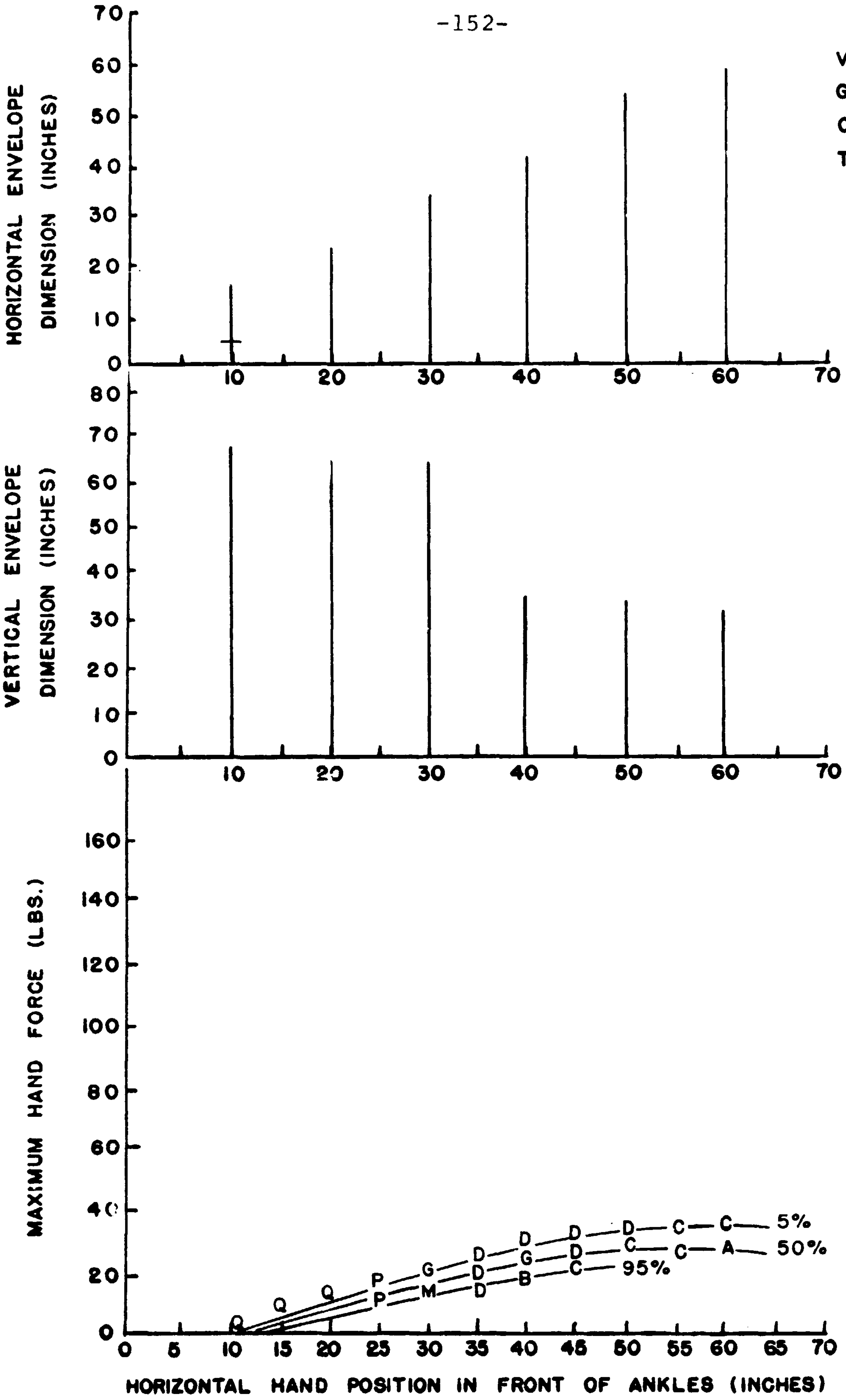
CLOTH: SHIRTSLEEVED

TASK: PUSHING



C-17

VERT: 30"
GRAV: 0.2 G
CLOTH: SHIRTSLEEVED
TASK: PUSHING



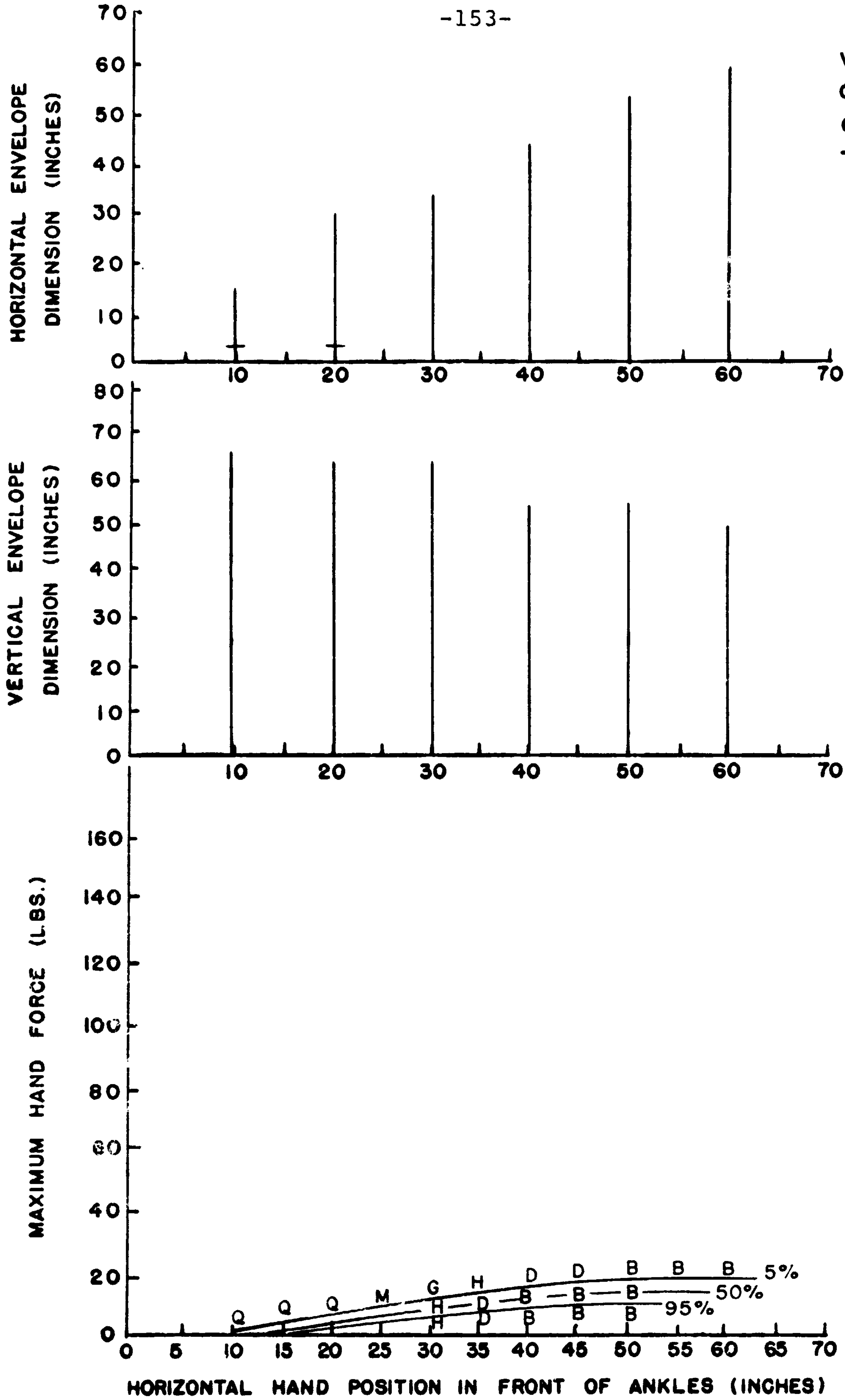
C-18

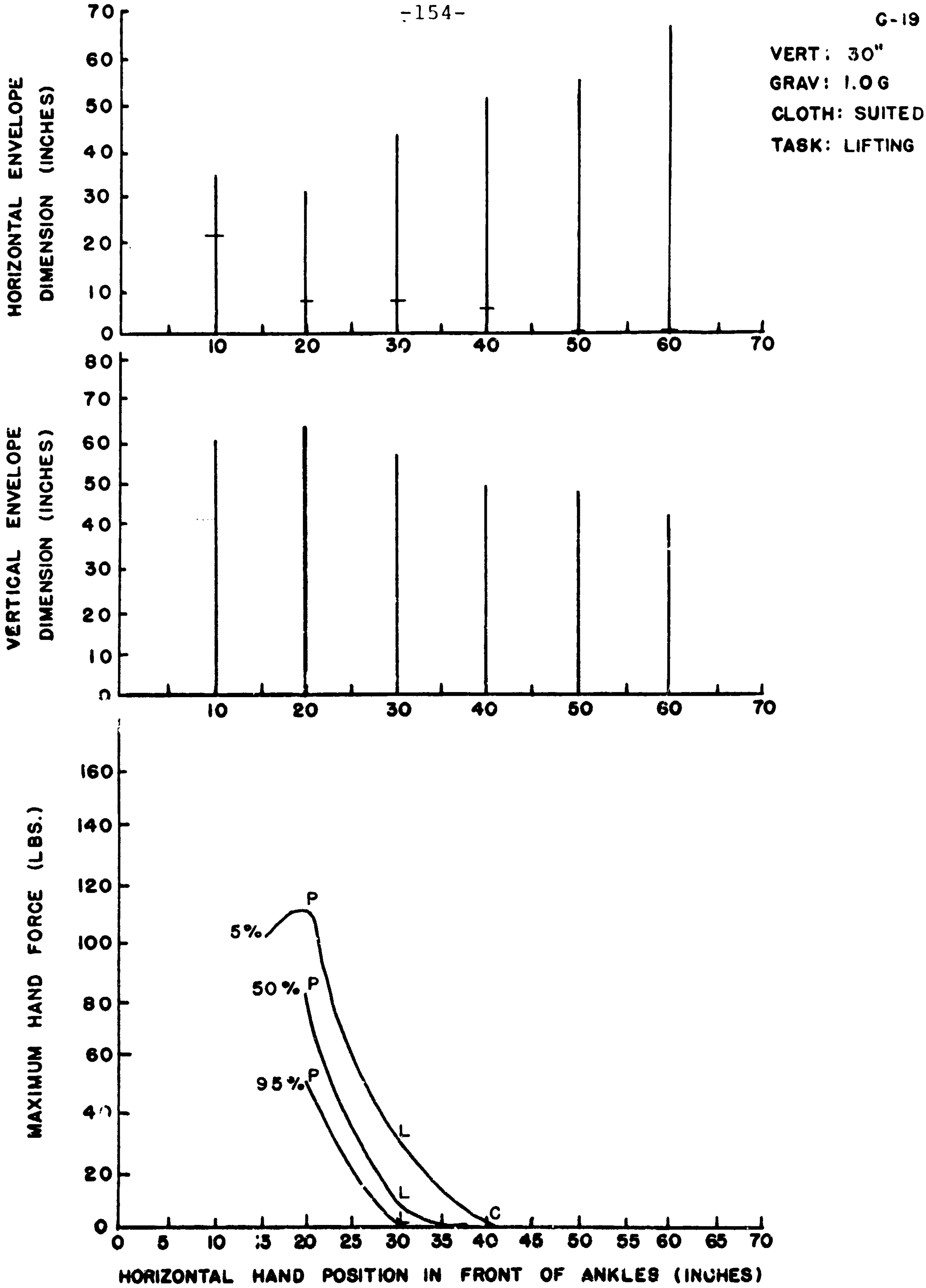
VERT: 50"

GRAV: 0.2 G

CLOTH: SHIRTSLEEVED

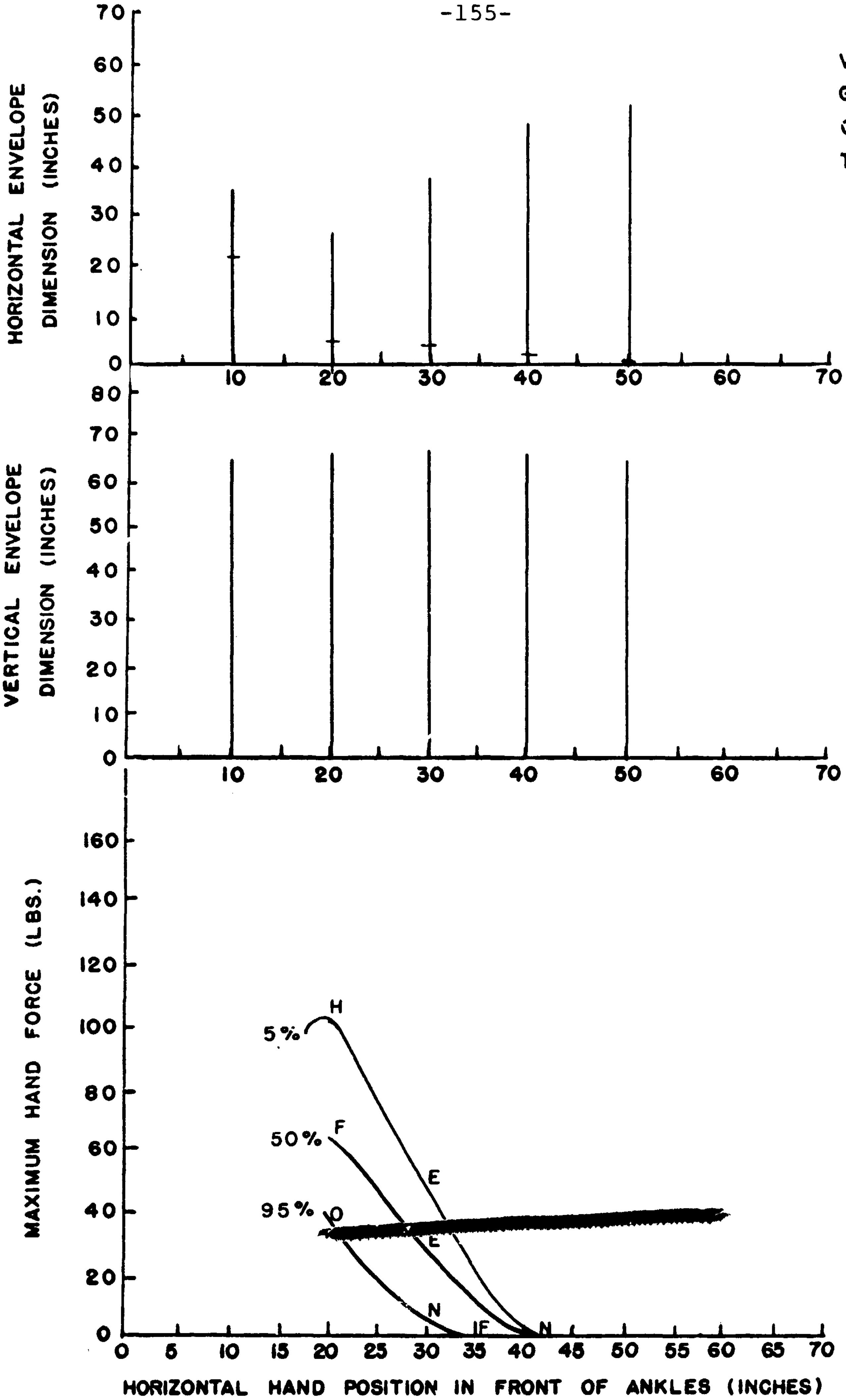
TASK: PUSHING




G-19
VERT: 30"
GRAV: 1.0 G
CLOTH: SUITED
TASK: LIFTING
HORIZONTAL ENVELOPE DIMENSION (INCHES)
VERTICAL ENVELOPE DIMENSION (INCHES)
MAXIMUM HAND FORCE (LBS.)
5%
50%
95%
P
L
C
HORIZONTAL HAND POSITION IN FRONT OF ANKLES (INCHES)

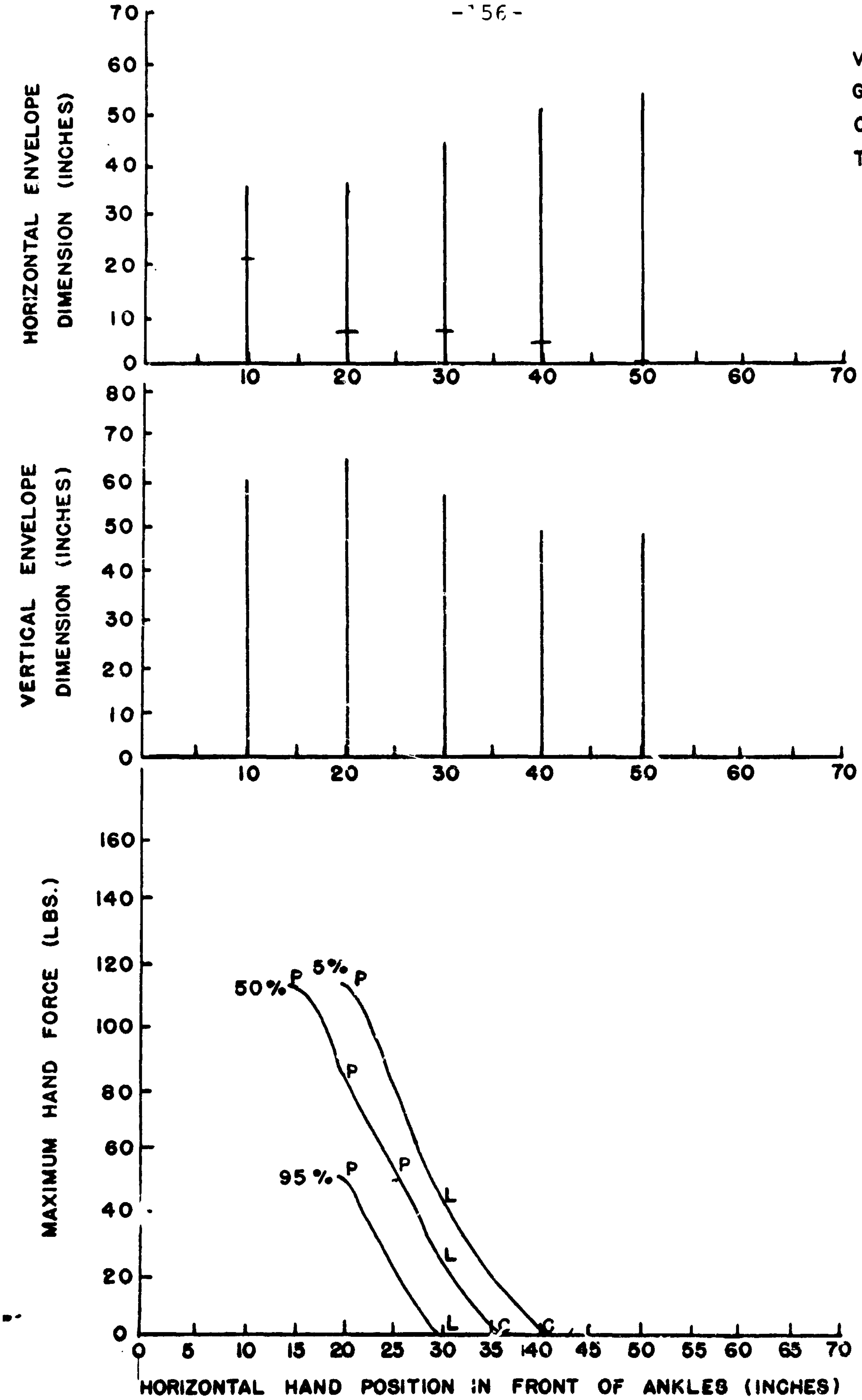
C-20

VERT: 60"
GRAV: 1.0G
CLOTH: SUITED
TASK: LIFTING



C-21

VERT: 30"
GRAV: 0.7 G
CLOTH: SUITED
TASK: LIFTING



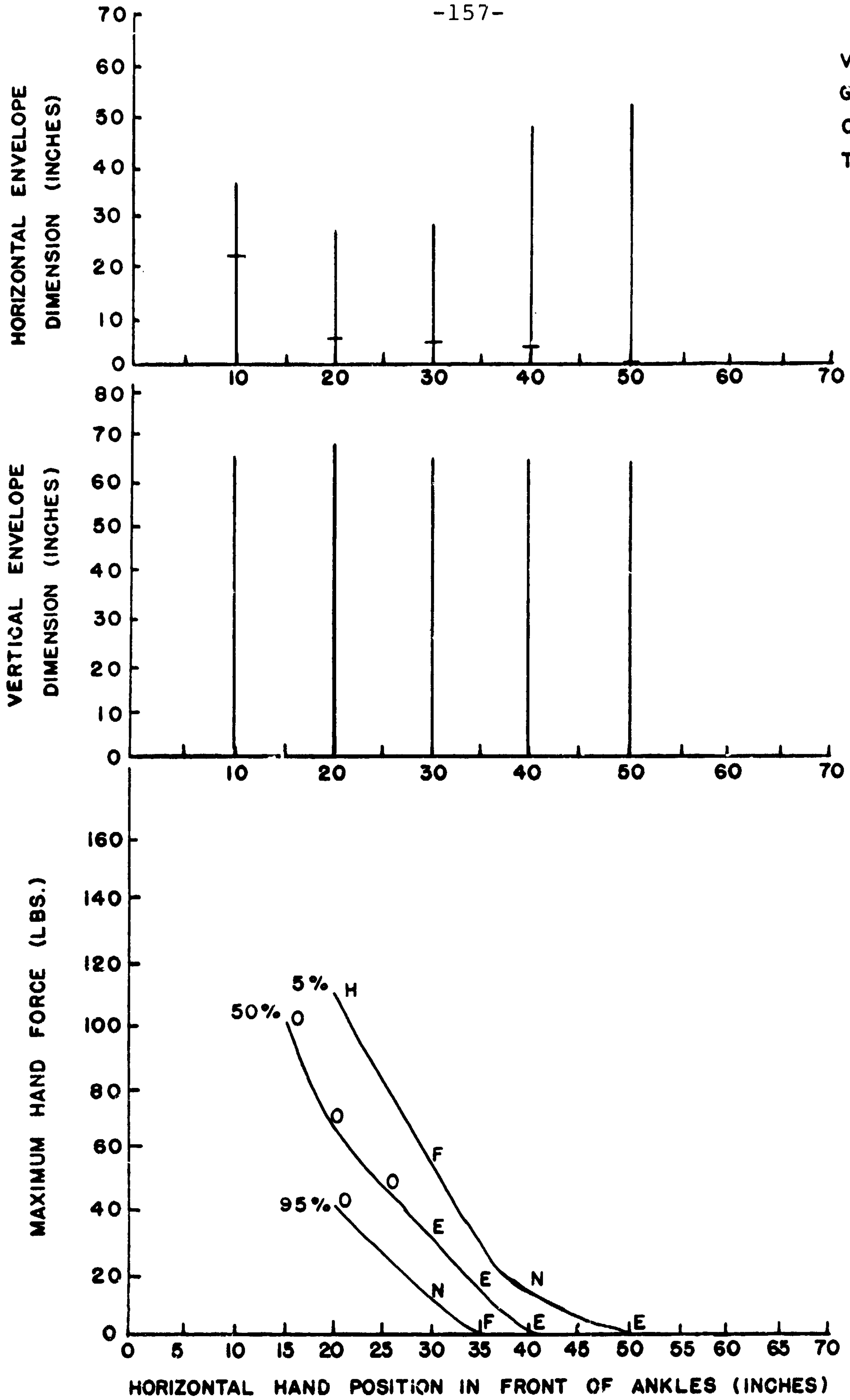
C-22

VERT: 60"

GRAV: 0.7G

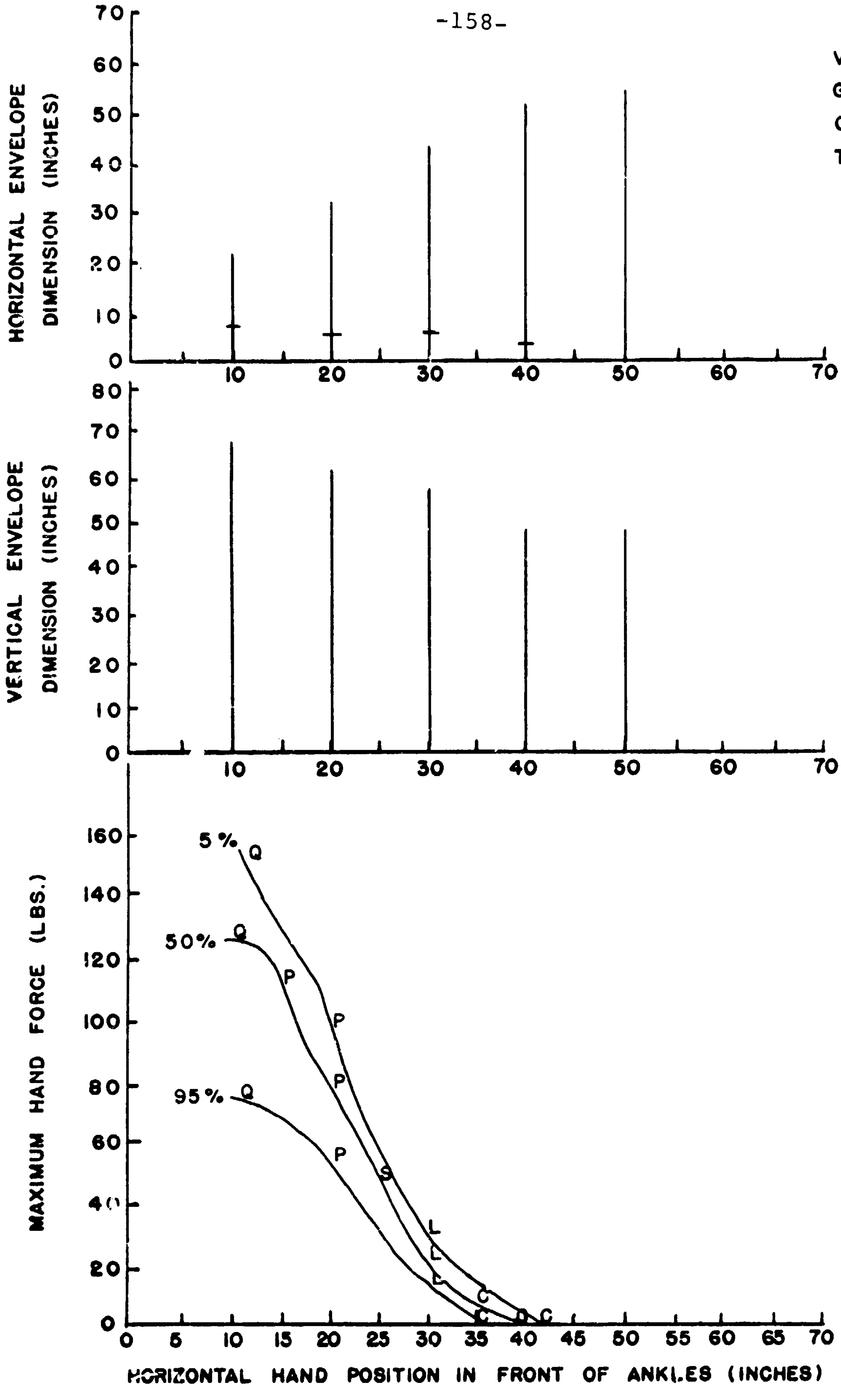
CLOTH: SUITED

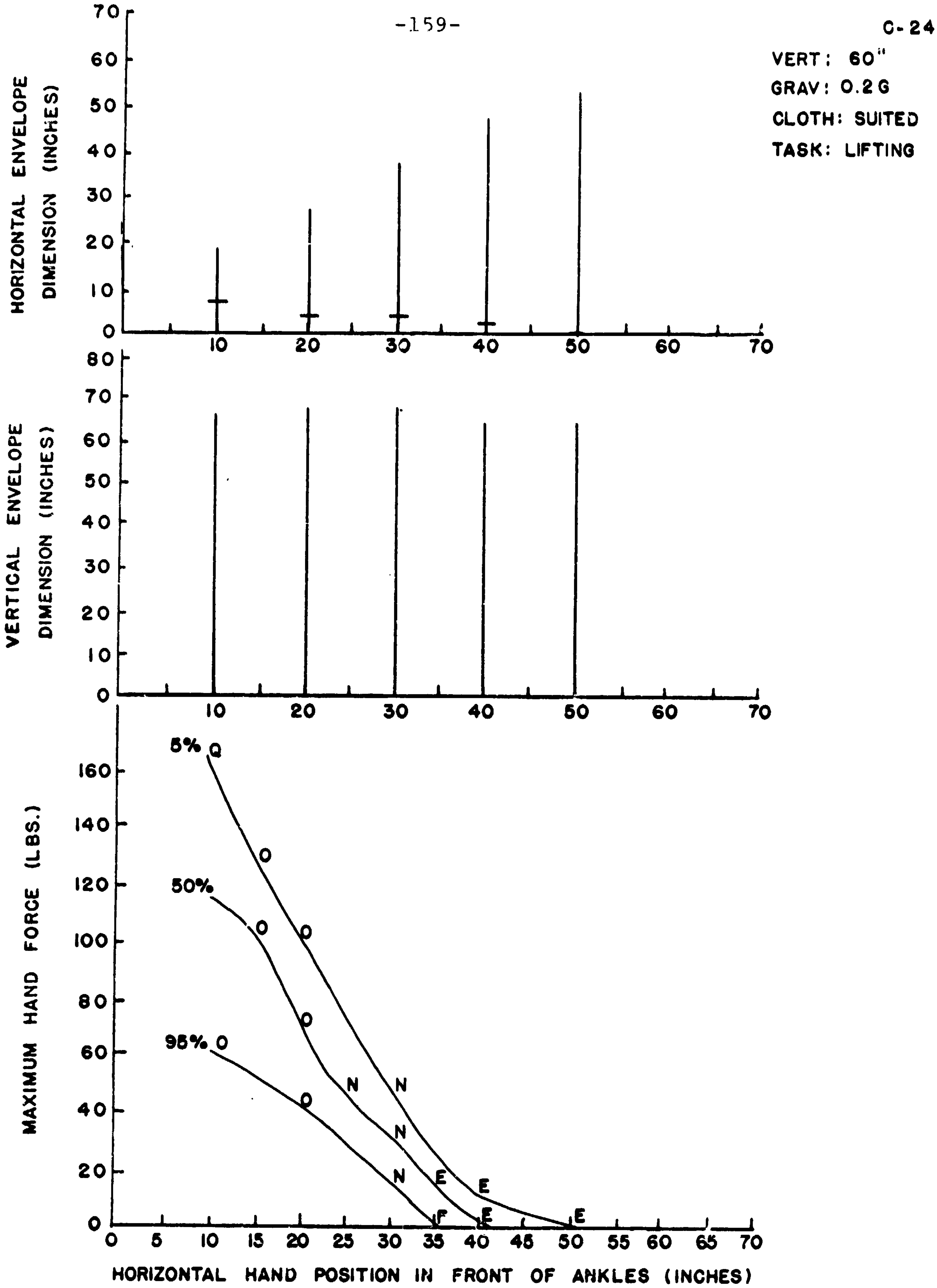
TASK: LIFTING



C-23

VERT: 30"
GRAV: 0.2 G
CLOTH: SUITED
TASK: LIFTING




C-24
VERT: 60"
GRAV: 0.2G
CLOTH: SUITED
TASK: LIFTING
HORIZONTAL ENVELOPE DIMENSION (INCHES)
VERTICAL ENVELOPE DIMENSION (INCHES)
MAXIMUM HAND FORCE (LBS.)
5%
50%
95%
HORIZONTAL HAND POSITION IN FRONT OF ANKLES (INCHES)

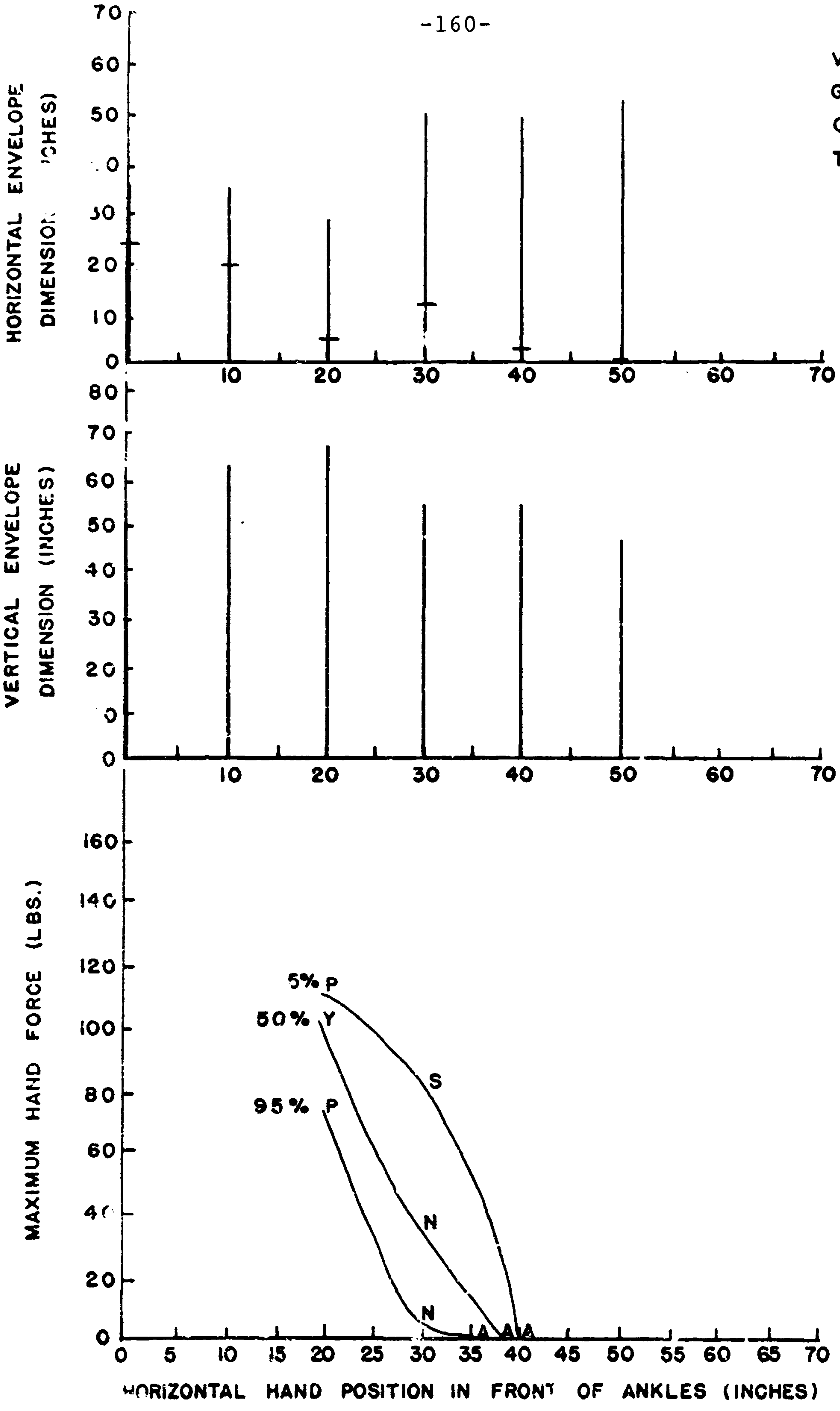
C-25

VERT: 40"

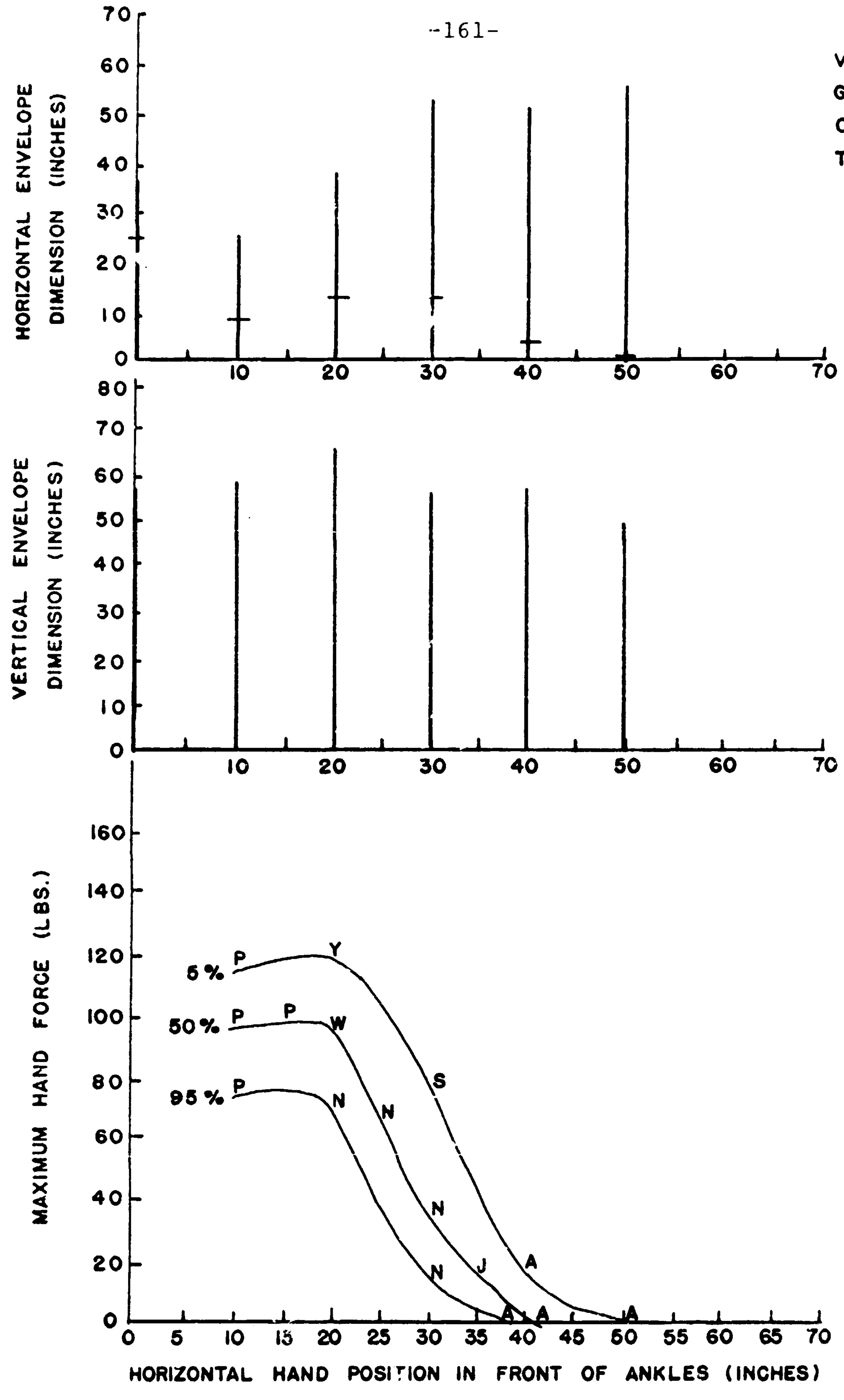
GRAV: 1.0 G

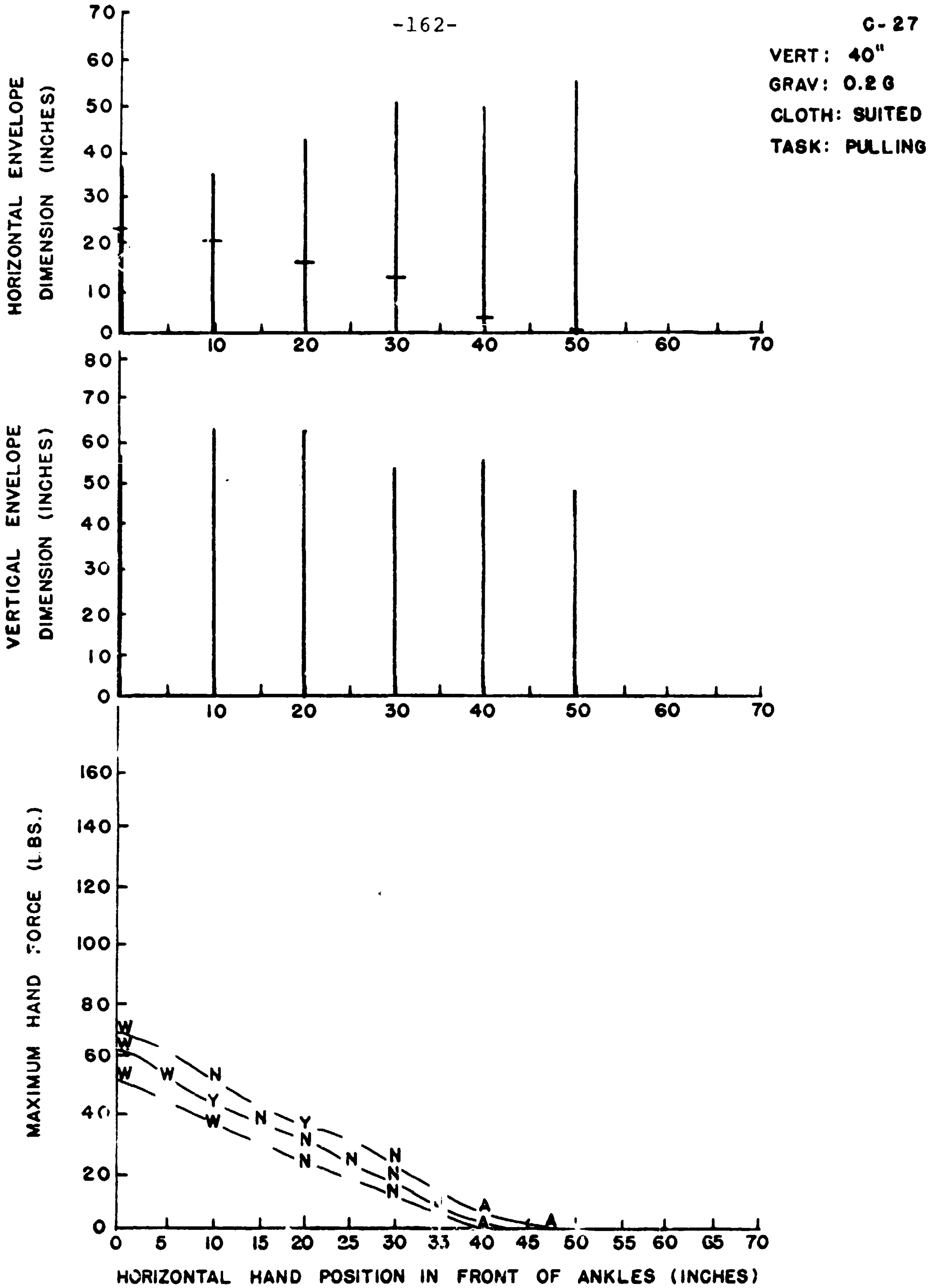
CLOTH: SUITED

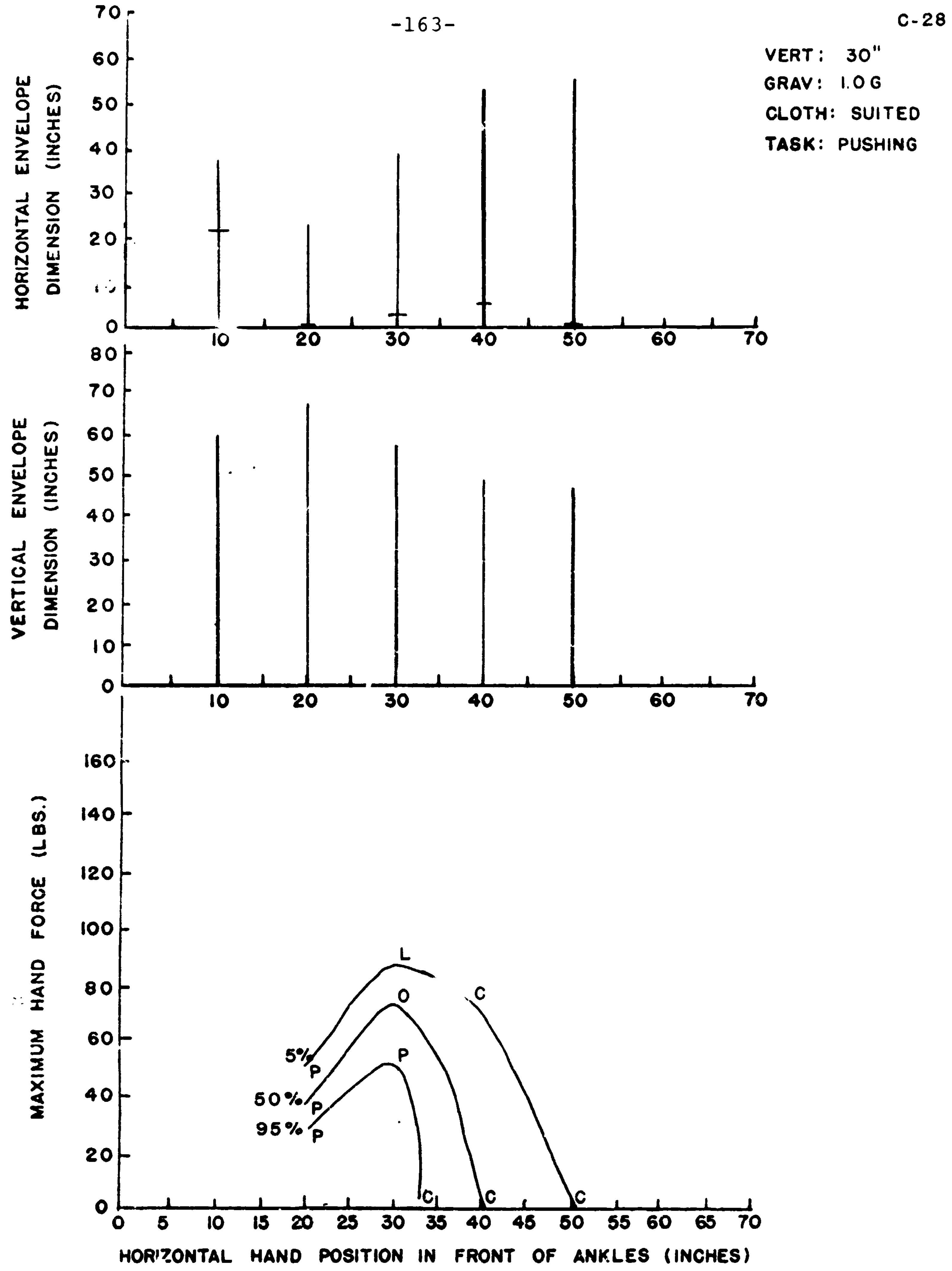
TASK: PULLING



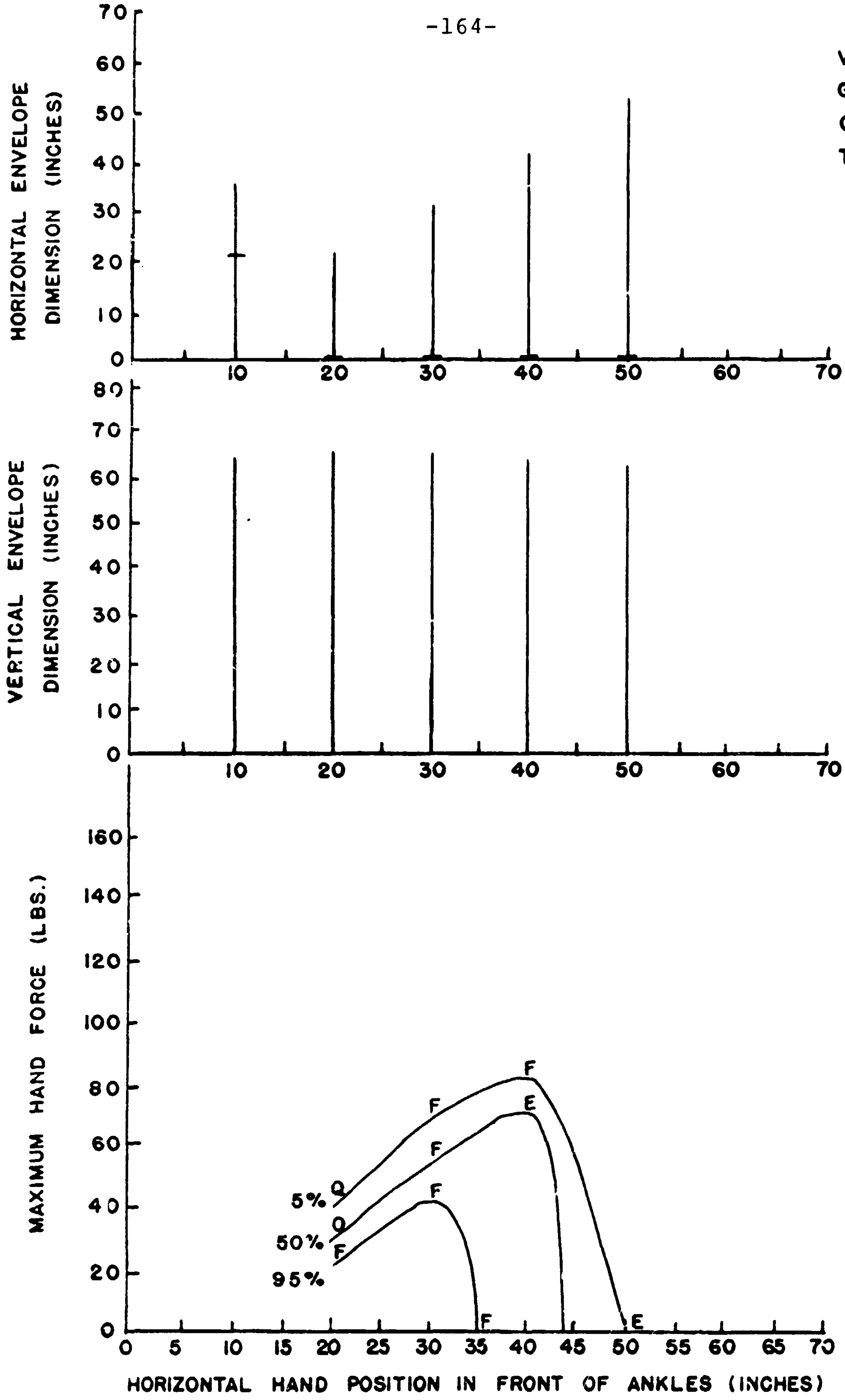
VERT: 40"
GRAV: 0.7 G
CLOTH: SUITED
TASK: PULLING




C-27
VERT: 40"
GRAV: 0.2 G
CLOTH: SUITED
TASK: PULLING
HORIZONTAL ENVELOPE DIMENSION (INCHES)
VERTICAL ENVELOPE DIMENSION (INCHES)
MAXIMUM HAND FORCE (LBS.)
HORIZONTAL HAND POSITION IN FRONT OF ANKLES (INCHES)


VERT: 30"
GRAV: 1.0 G
CLOTH: SUITED
TASK: PUSHING
HORIZONTAL ENVELOPE DIMENSION (INCHES)
VERTICAL ENVELOPE DIMENSION (INCHES)
MAXIMUM HAND FORCE (LBS.)
L
O
P
C
5%
50%
95%
HORIZONTAL HAND POSITION IN FRONT OF ANKLES (INCHES)

VERT: 60"
GRAV: 1.0 G
CLOTH: SUITED
TASK: PUSHING



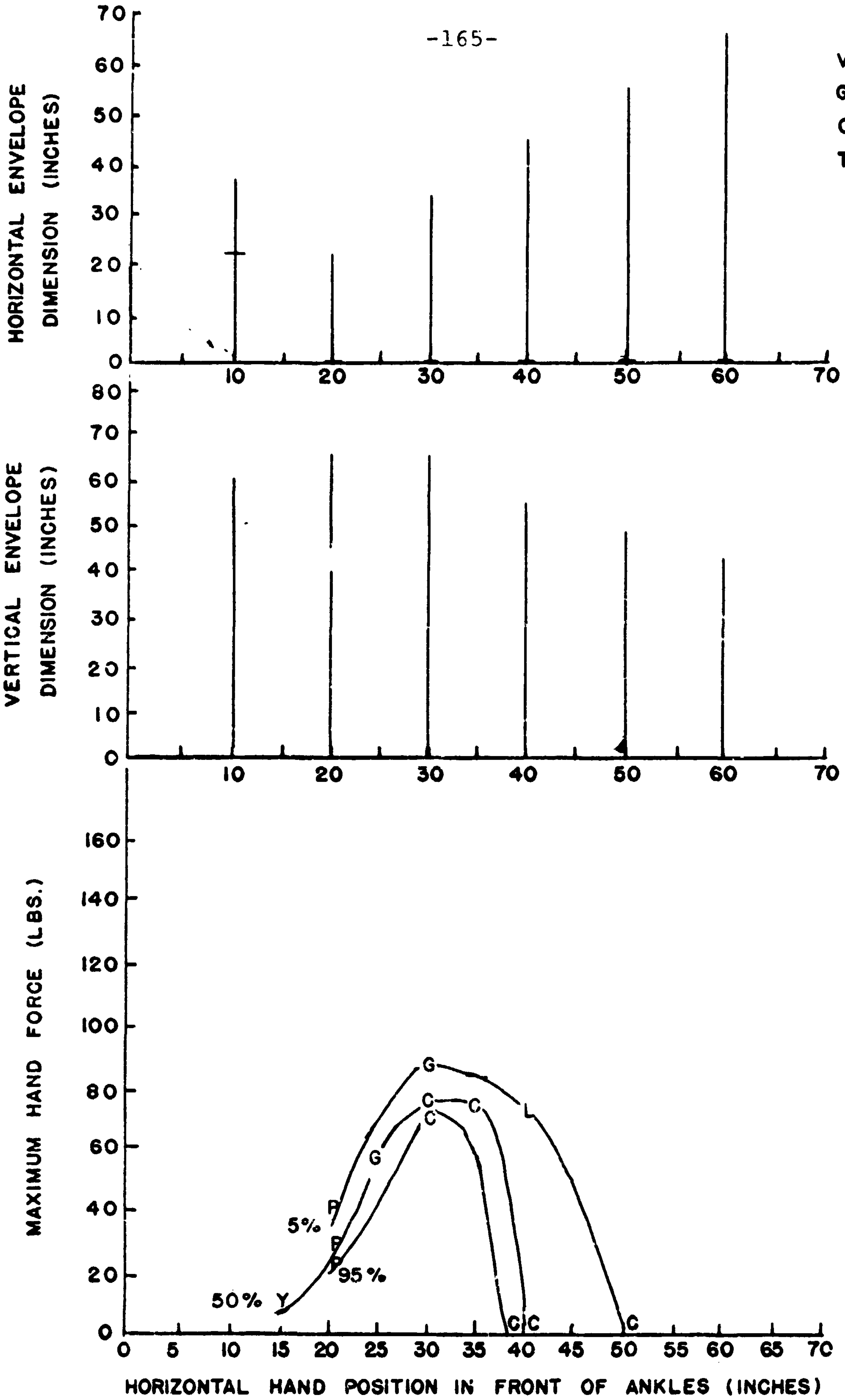
C-30

VERT: 30"

GRAV: 0.7 G

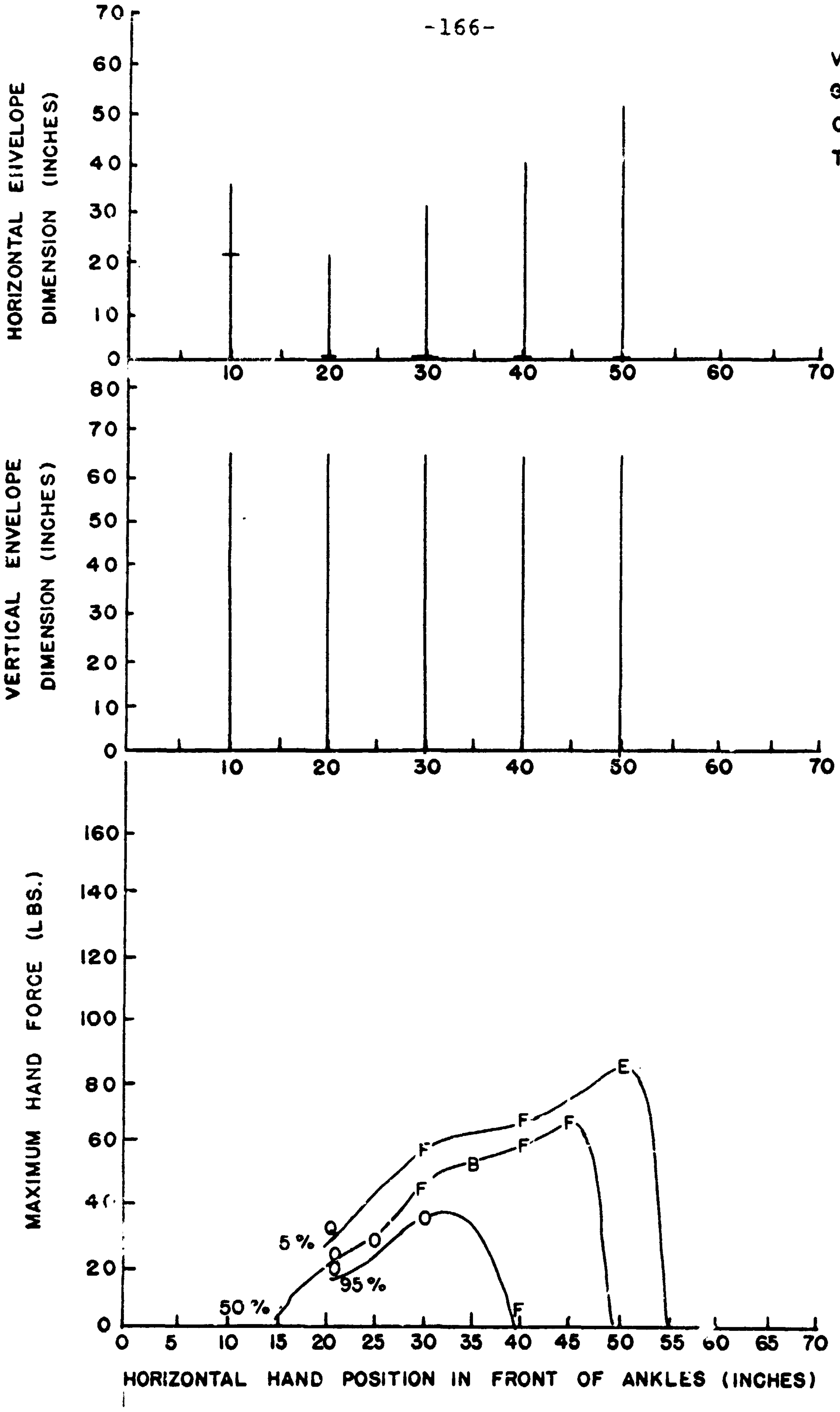
CLOTH: SUITED

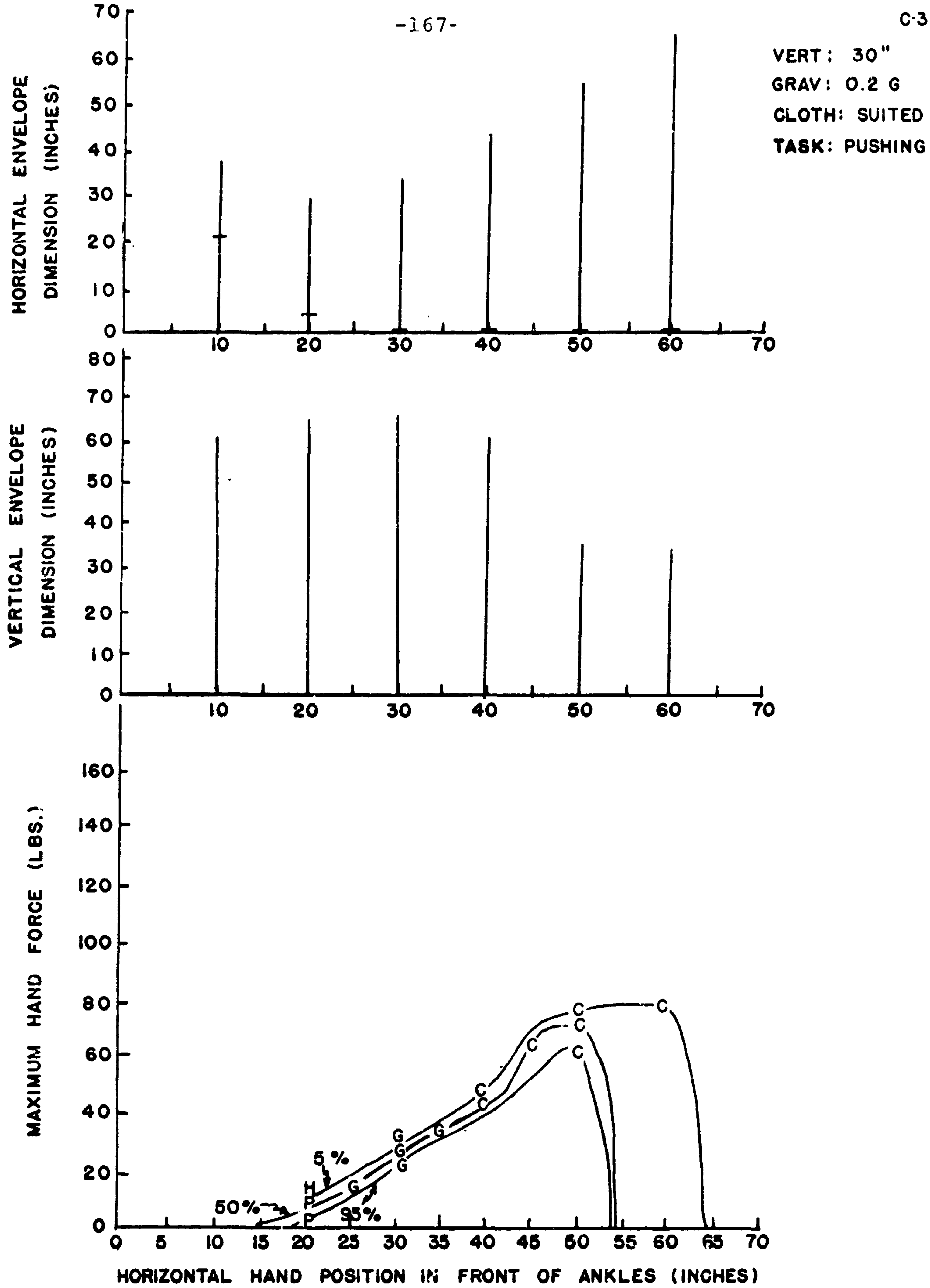
TASK: PUSHING



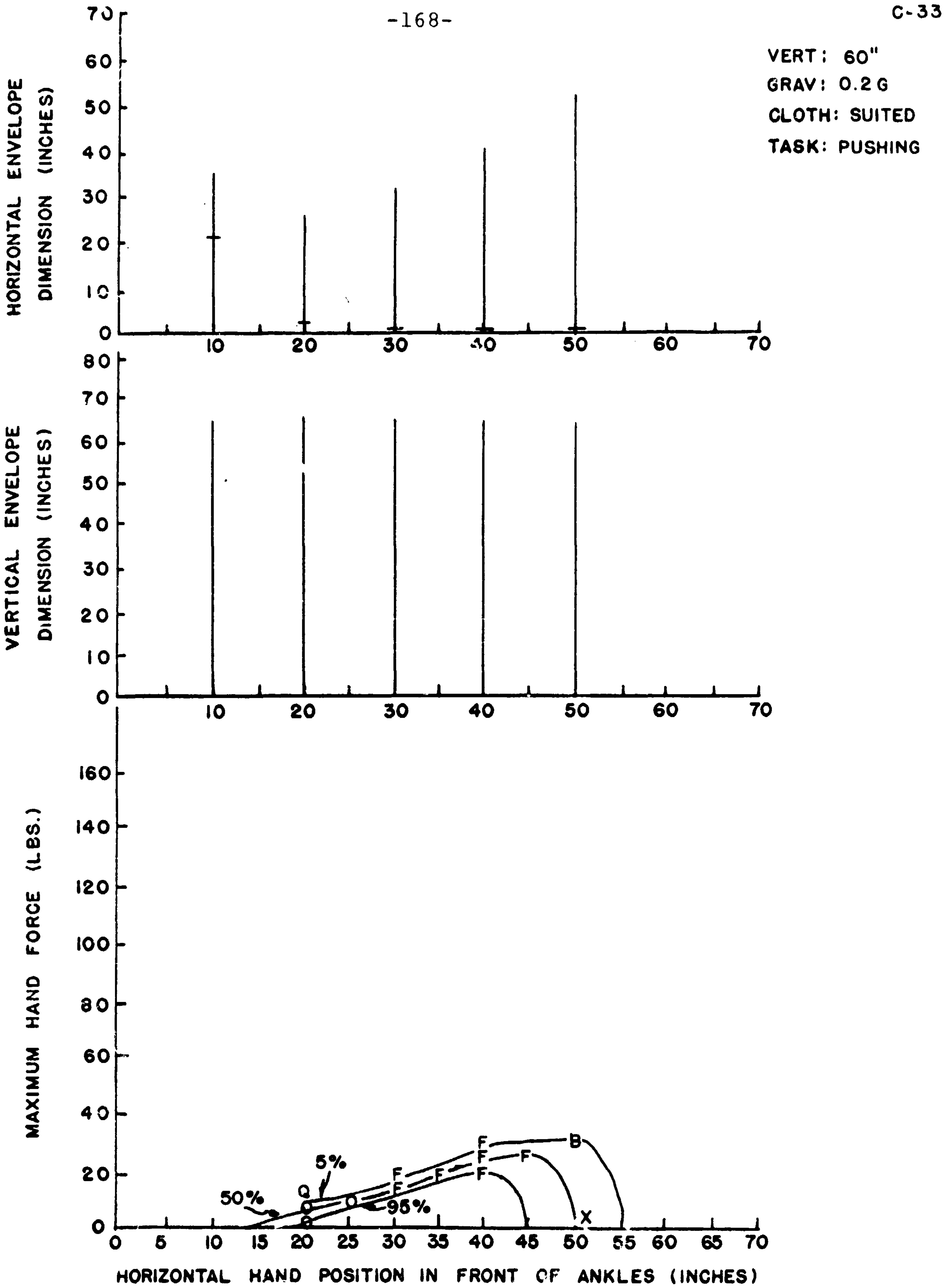
C-31

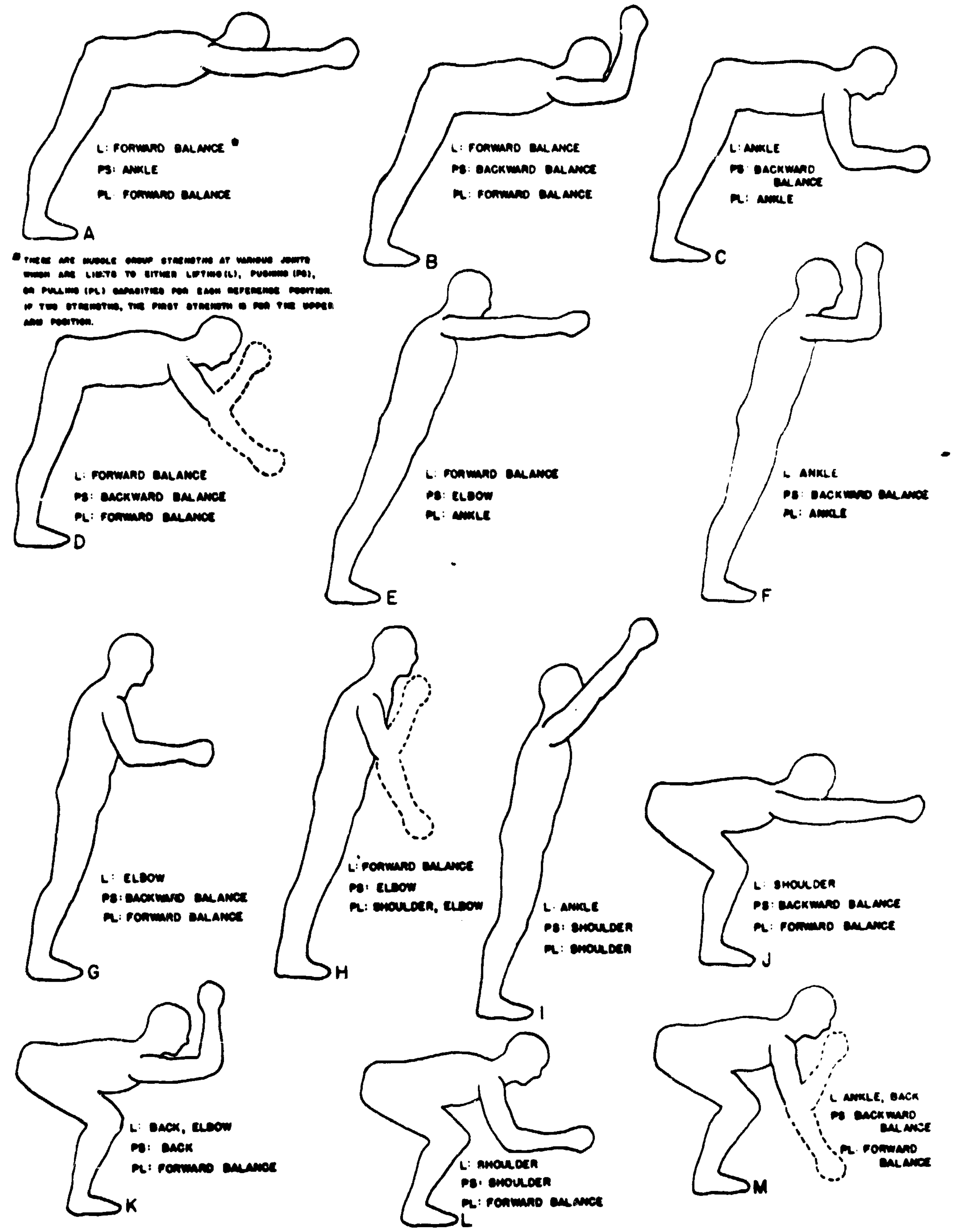
VERT: 60"
GRAV: 0.7G
CLOTH: SUITED
TASK: PUSHING



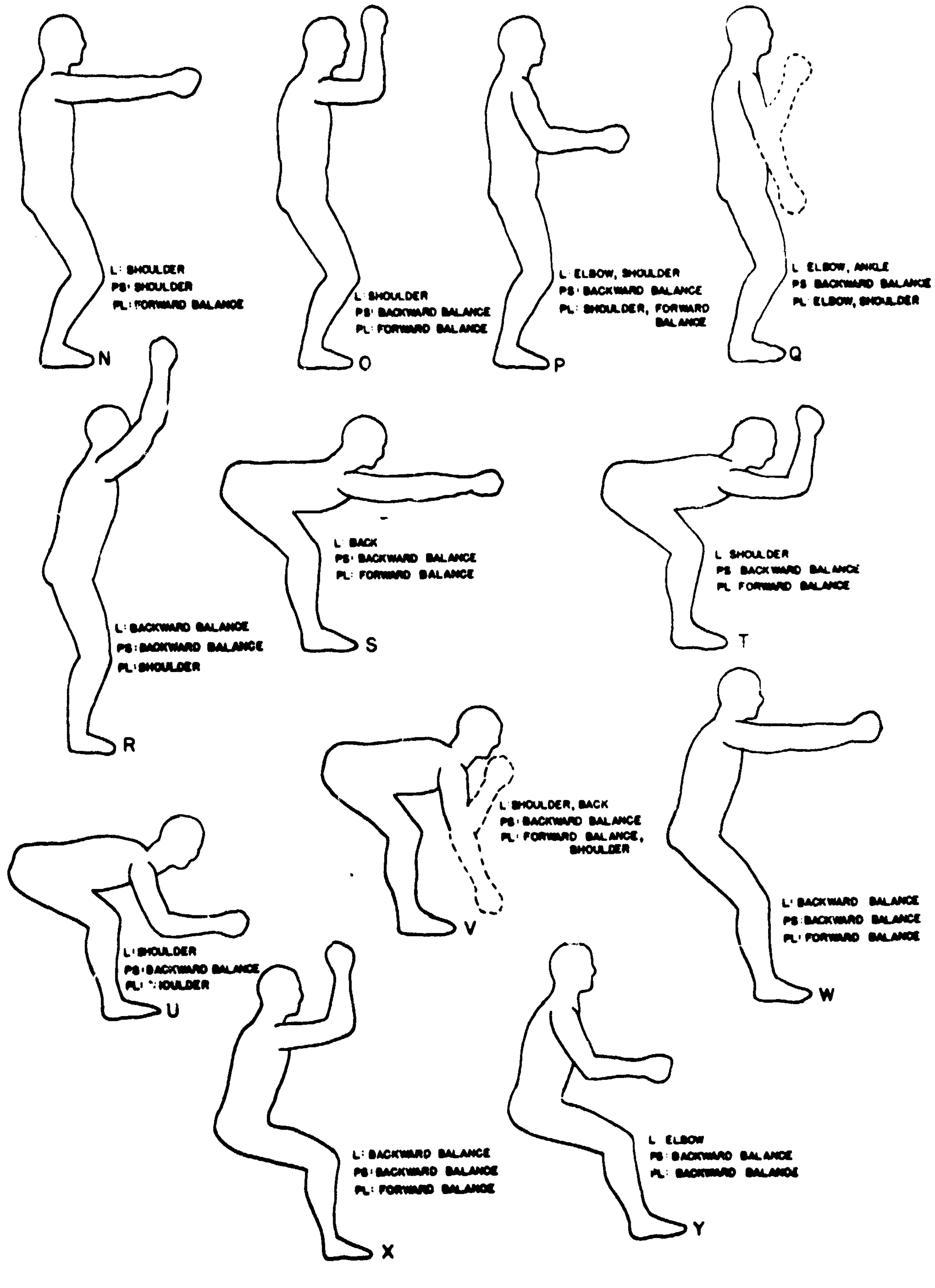


VERT: 30"
GRAV: 0.2 G
CLOTH: SUITED
TASK: PUSHING
HORIZONTAL ENVELOPE DIMENSION (INCHES)
VERTICAL ENVELOPE DIMENSION (INCHES)
MAXIMUM HAND FORCE (LBS.)
HORIZONTAL HAND POSITION IN FRONT OF ANKLES (INCHES)
5%
50%
95%

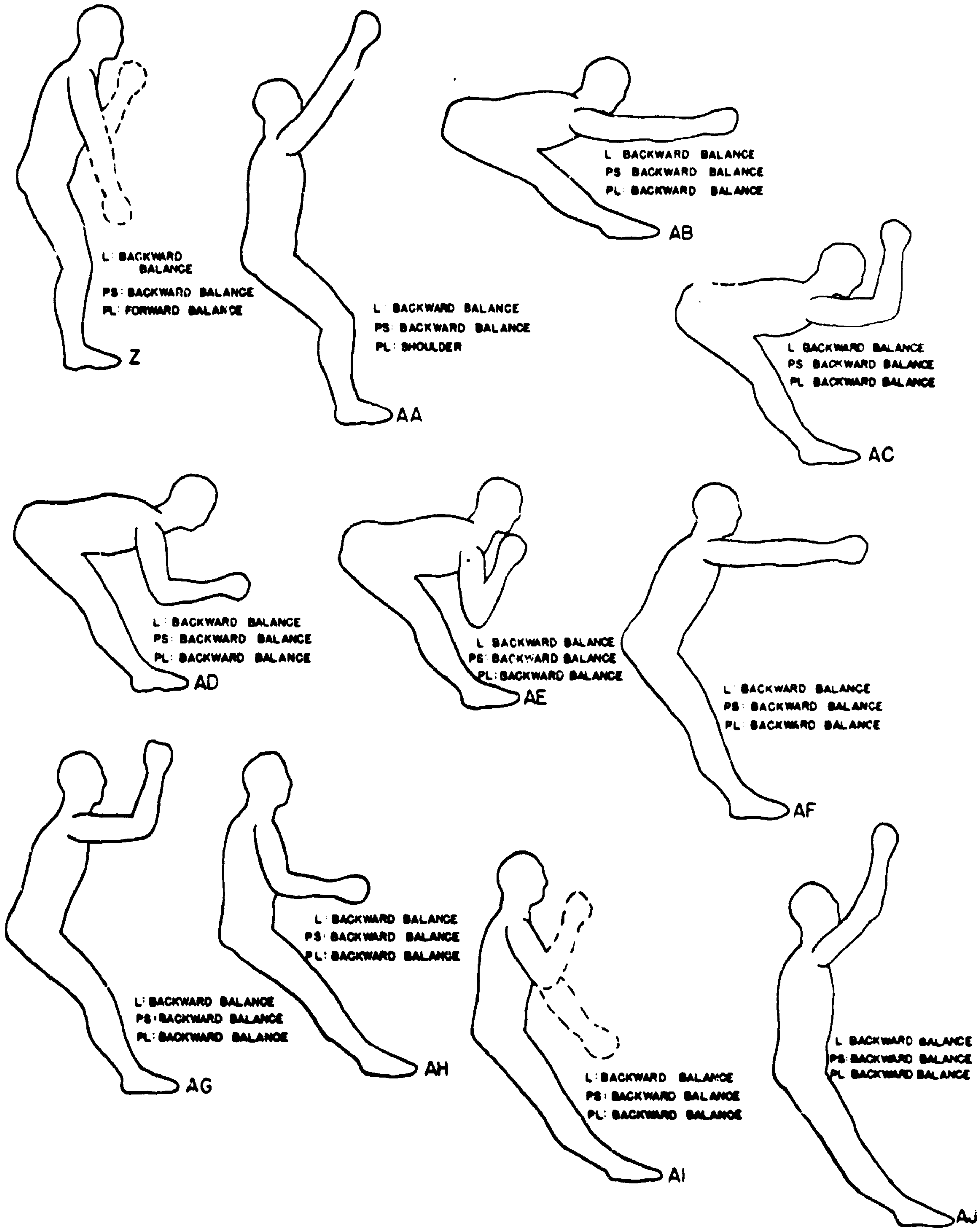

VERT: 60"
GRAV: 0.2 G
CLOTH: SUITED
TASK: PUSHING
HORIZONTAL ENVELOPE DIMENSION (INCHES)
VERTICAL ENVELOPE DIMENSION (INCHES)
MAXIMUM HAND FORCE (LBS.)
5%
50%
95%
HORIZONTAL HAND POSITION IN FRONT OF ANKLES (INCHES)



STANDARD BODY POSITIONS



STANDARD BODY POSITIONS (CONT.)



STANDARD BODY POSITIONS (CONT.)